PHASE 2 PEAT PROGRAM

Hydrological Factors of Peat Harvesting

FINAL REPORT

PHASE II - PEAT PROGRAM

HYDROLOGIC FACTORS OF PEAT HARVESTING

Principal Investigator: Kenneth N. Brooks

Graduate Research Assistant: Steven R. Predmore

Department of Forest Resources
College of Forestry
University of Minnesota

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1 Northern Conifers Laboratory, North Central Forest Experiment Station, U.S. Forest Service, Grand Rapids, Minnesota.

2 Department of Soil Science, University of Minnesota.

3 Minnesota Department of Natural Resources.

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SUMMARY

This report describes the hydrologic characteristics of natural peatlands, methods of peat harvesting, and the expected impacts of peat harvesting on water resources. Lake States, Canadian and European experiences are reviewed and coupled with the characteristics of Minnesota peatlands to estimate harvesting impacts.

Based on their hydrogeologic relationship, peatlands are classified as ombrotrophic bogs or minerotrophic fens. Ombrotrophic bogs are isolated from the regional groundwater aquifer and receive water and nutrients primarily from precipitation. Streamflow from ombrotrophic bogs exhibits greater seasonal variability than minerotrophic fens; fens are an integral part of the regional groundwater systems, thus streamflow fluctuates primarily in response to groundwater changes. Maximum annual flows from ombrotrophic and minerotrophic peatlands usually occur in the spring or early summer. Increased evapotranspiration during summer months reduces the water table elevation and discharge.

Contrary to popular belief, peatlands do not act as large reservoirs which store water during wet periods and release water during dry periods. Water flow through and from peatlands is governed by the physical properties and hydraulic characteristics of peat soils. Surface peats are least decomposed, have the highest porosity, and exhibit the highest rates of water movement. Decomposition, bulk density, and water retention increase and hydraulic conductivity decreases with depth. The elevation of the water table (either perched or regional) within a peat-soil profile

determines base flow. Runoff from a given storm event is relatively rapid because the undecomposed peat surface is often saturated, permits rapid water movement, and is underlain by denser peats which restrict the downward movement of precipitation. The flat topography associated with peatlands is largely responsible for peak-flow attenuation.

Ombrotophic bogs yield water of low pH and low mineral content, particularly calcium. Minerotrophic fens yield more neutral water of a high mineral content. Although Minnesota contains extensive minerotrophic fens, both lake-filled and built-up, most water quality and other hydrologic studies have been conducted on ombrotophic, lake-filled peatlands.

The methods of peat harvesting most likely utilized in Minnesota, are considered in this study. These methods include 1) sod peat, 2) milled peat, 3) shaved peat, 4) hydraulic dredge, 5) hydro-jet and 6) dragline excavation. Our analysis separated the methods into those requiring drainage (1-3) and those not requiring drainage (4-6).

The hydrologic effects of peat harvesting are not well documented and study results have often been conflicting. Therefore, impacts of peat harvesting on water yield and water quality characteristics of the harvest site are estimated by determining and summing the effects of each step in the harvesting process. The total hydrologic impact, however, would depend on the size and location of the harvest site within a watershed.

The hydrologic effects from drained methods would be due to vegetation removal, drainage, and peat extraction. The combined effects of these activities could result in increased annual water yield and increased maximum discharges. Effects on minimum flow are difficult to estimate. The effects of undrained methods would likely depend upon the presence or absence of an outlet from the pond created by peat extraction. Assessments of water yield changes are tied closely to assumptions of evapotranspiration losses before and after harvesting; these assumptions need to be tested with field research.

Drained harvesting methods may result in increased concentrations of organically derived nutrients, humates, and particulate organic matter in discharge waters. Undrained impacts would again be associated with the presence or absence of an outlet. The addition of nutrient enriched discharge waters and particulate material transported by wind to receiving waters could conceivably promote increased eutrophication of receiving waters. Baseline and post-harvesting water quality analyses are needed to test these hypotheses.

Methods or models need to be developed which can predict the quantity and quality of water yielded from undistrubed and harvested peatlands. Such methods would provide decision makers with hydrologic information critical to the selection of alternatives which are in the best interest of Minnesota.

INTRODUCTION

Widespread harvesting of peat and the subsequent impacts on Minnesota's water resources are the concerns of this report. Although few of the State's approximately 7.5 million acres of peatlands are presently being harvested for horticultural peat, more extensive use seems inevitable. An example of the potential demand for this resource is the Minnesota Gas Company's (Minnegasco) proposal to harvest 200,000 acres to supply a peat gasification facility (Boffey, 1975). Questions concerning the effects of such extensive harvesting on the water resource were raised because of the close association between peatlands and water.

This study is the first step in a comprehensive assessment of the effects of peat harvesting on water quantity and quality. To make such an assessment, European experiences were examined. These experiences were then coupled with limited information concerning the hydrologic characteristics of Minnesota peatlands to estimate harvesting effects. Information and research needed for a more rigorous assessment of the hydrologic consequences will also be discussed. Specific objectives were to:

(1) Identify and evaluate factors and processes which govern the hydrologic responses of Minnesota peatlands.

(2) Synthesize European experiences and the hydrologic characteristics of Minnesota peatlands to estimate possible impacts of peat harvesting on the quantity and quality of water yield.

(3) Determine the hydrologic process and components of a model capable of predicting the hydrologic response of peatlands in Minnesota.

HYDROLOGY OF NATURAL PEATLANDS

The hydrologic response of a peatland depends upon climate, vegetation, topography and the physical properties of the peat (Vidal, 1960). Climate determines the inputs of a hydrologic system through precipitation which can vary in terms of quantity, intensity, duration, and physical state. Climate also influences evapotranspiration losses from the hydrologic system through energy influx. Peatland formation and organic matter accumulation depends upon precipitation exceeding evapotranspiration. This results in saturated conditions which inhibit microbial decomposition of peat material.

Peatland vegetation and its influence on evapotranspiration losses affect peatland hydrology. Subsurface water is transpired which can lower peatland water levels. Vegetation also intercepts precipitation which is then evaporated to the atmosphere. These processes represent losses to runoff or groundwater.

Flat topography characterizes most peatlands with micro-relief features which may affect water movement (Vidal, 1960). Convex surfaces, hummocks and hollows, and depression tracks found in different peatlands influence runoff processes and infiltration of precipitation (Dooge, 1975).

The rate of water movement and water retention characteristics in peat soils are largely determined by the degree of decomposition and bulk density of peat (Boelter, 1969). These properties influence the hydraulic conductivity as shown in Figure 1. As the degree of decomposition decreases (from sapric to fibric) hydraulic conductivity increases. Similarly,

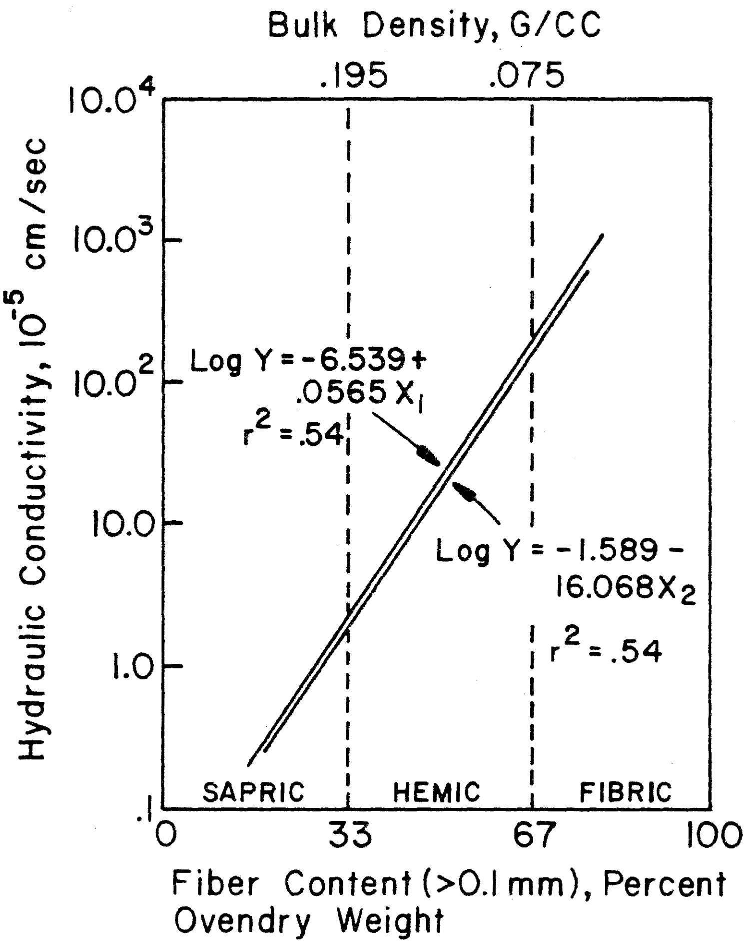

Figure 1. Relationships between hydraulic conductivity and bulk densities of peat soils of differing decomposition. (From Boelter, 1969.)

hydraulic conductivity is low for peat of high bulk density and increases for peat of low bulk density. Although hydraulic conductivity is directly related to pore size, water retention is inversely related to pore size. Sapric peats of high bulk density and predominately small pores hold and retain greater amounts of water than the more undecomposed, loose peats (Figure 2).

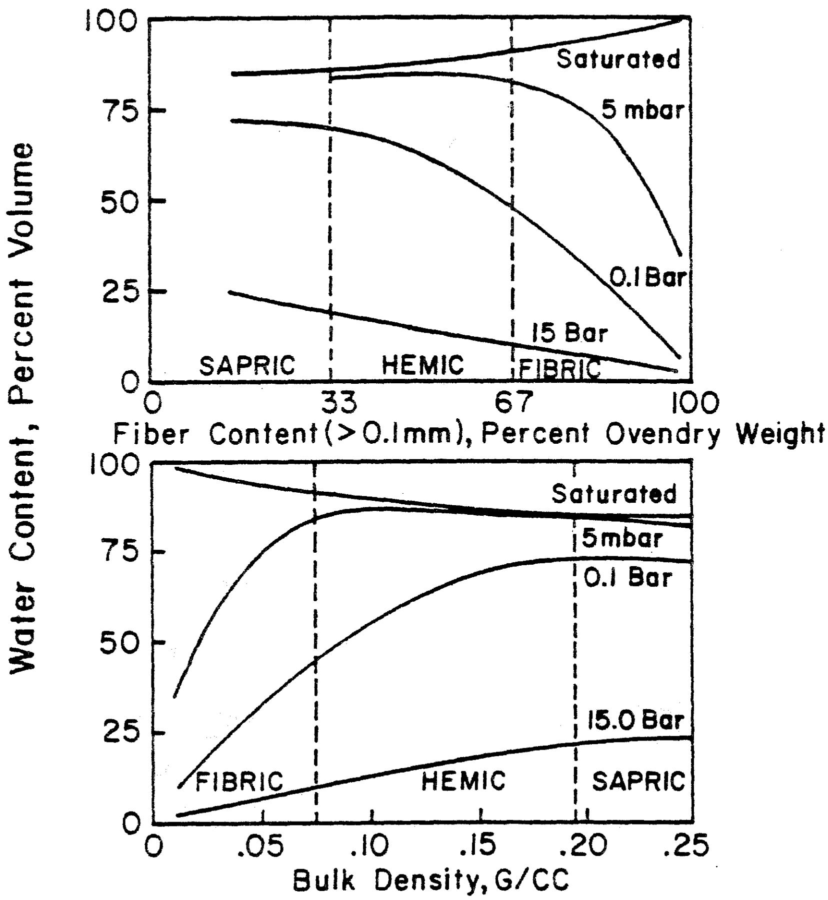

Figure 2. Relationships between fiber content, bulk density, and water content for different types of peat at various suctions. (From Boelter, 1969.)

Water retention values are important because they determine the amount of precipitation which may be stored in the peat soil (Figure 3). Hydraulic conductivity , on the other hand, governs the rate of water movement within the soil. When precipitation intensities exceed the rate at which water can flow into and through the soil, water will flow over the surface or through the loose fibric peat in the upper soil profile.

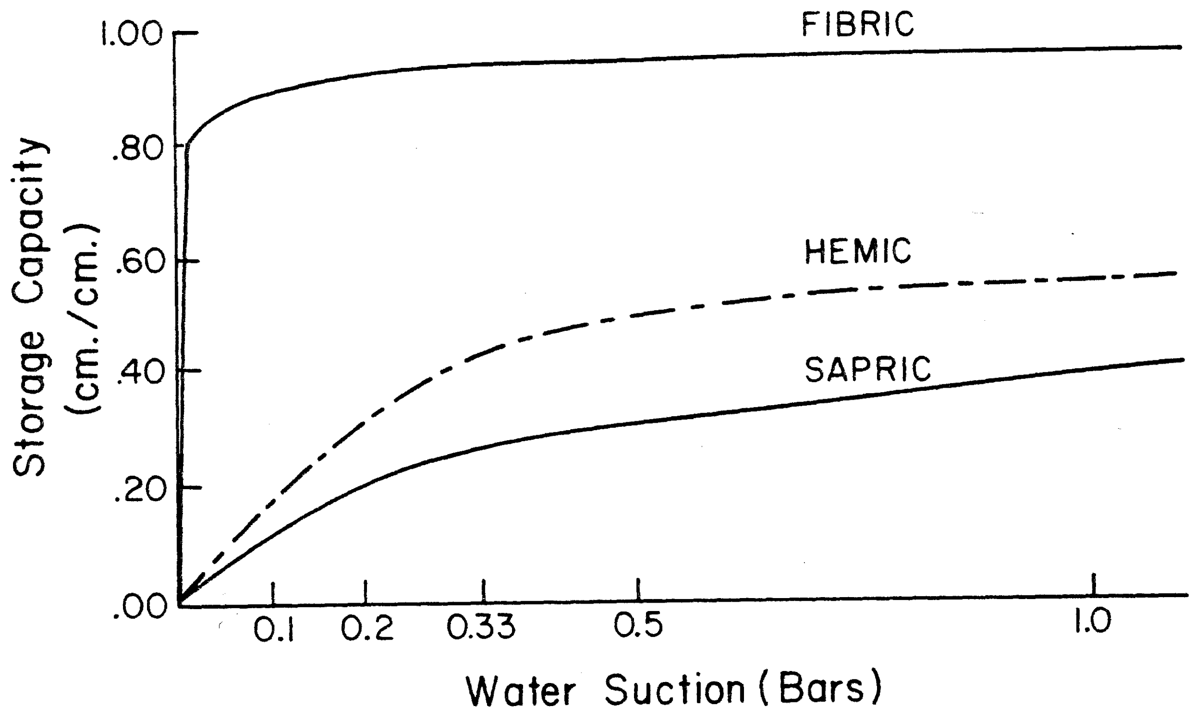

Figure 3. Available moisture storage capacity as related to peat type at various suctions. (Modified from Boelter, 1964.)

In addition to the above factors, the hydrogeology of a peatland is also important in determining hydrologic response. Here we refer to the relationship between the regional groundwater and the peatland water table. Based on hydrogeology, peatlands may be generally categorized as either ombrotrophic or minerotrophic. The water table within an ombrotrophic peatland is isolated from the regional groundwater aquifer and receives inputs primarily by precipitation. These peatlands are often referred to as bogs. Minerotrophic peatlands, on the other hand, intersect the regional groundwater aquifer and receive inputs from precipitation plus groundwater inflow from surrounding mineral soils. Such peatlands are referred to as fens. Some peatlands may be considered transitions between ombrotrophic and minerotrophic depending on the amount of groundwater inflow. These classifications are important because both quantity and quality of outflow are the result of the hydrogeologic relationships discussed.

Water Yield Characteristics

Many of Minnesota's peatlands have developed through the accumulation of organic material in lakes which were originally glacial ice-block depressions (Boelter and Verry, 1977). These peatlands may be ombrotrophic or minerotrophic. Many ombrotrophic lake-filled peatlands are isolated above the regional groundwater aquifier and referred to as perched bogs. Perched bogs receive the majority of their water directly from precipitation, although some snowmelt and runoff from mineral soil uplands may also occur. Surface peats are generally undecomposed sphagnum moss underlain by more decomposed peats (Table 1). Minerotrophic lake-filled peatlands, due to groundwater inflow, often support sphagnum and non-sphagnum vegetation and may also exhibit increased decomposition with depth.

The Glacial Lake Agassiz peatlands in northwest Minnesota are not lake-filled but built-up peatlands formed on flat areas as a result of rising water levels caused by peat accumulation. These peatlands are extensive and comprised of both ombrotrophic and minerotrophic areas (Heinselman, 1963). Centrally located regions, far removed from mineral

Table 1. An organic soil profile from a lake-filled ombrotrophic or perched bog (Boelter and Verry, 1977).

Horizon label & depth	Horizon description	Fiber content	Bulk density	Soil pH in H_2O
cm		*percent*	*g/cm^3*	
A 0 to 15	Fibric peat--undecomposed sphagnum moss and leaves of heath shrubs.	90 to 98	0.015 to 0.028	4.2
B 15 to 30	Fibric peat--relatively undecomposed sphagnum moss and roots of heath shrubs.	70 to 80	0.050 to 0.075	4.2
C 30 to 45	Hemic peat--moderately to well decomposed sphagnum moss with wood inclusions.	40 to 45	0.08 to 0.19	4.4
D 45 to 60	Sapric peat--well decomposed aggregrated peat with no recognizable plant remains.	15 to 30	0.21 to 0.26	4.1
E 60 to 100	Hemic peat--moderately decomposed herbaceous peat from reeds and sedges.	40 to 55	0.12 to 0.17	4.8
100 to 200	Hemic peat--moderately decomposed sedge peat.	--	--	5.4
200 to 225	Sapric peat--well decomposed aquatic peat mixed with considerable sand.	--	-- (very dense)	5.3
225+	Lacustrine silt and clay.	--	--	5.4

soils, receive water primarily by precipitation. Minerally influenced water, derived from mineral soil runoff and the regional groundwater aquifer, is associated with the peatland perimeter and areas of rapid water movement. Ombrotrophic areas consist principly of sphagnum in the upper layers with variable underlying peats. Minerally influenced areas, on the other hand, consist of moderately to highly decomposed peat. Because of the complexity and extensiveness of the Glacial Lake Agassiz peatlands, much less is known of their hydrology as compared to lake-filled peatlands. The following discussion of water yield attempts to simplify matters by focusing primarily on lake-filled peatland hydrology for which much more information is available. Ombrotrophic and minerotrophic areas within the Lake Agassiz peatlands may be hydrologically similar to their counterparts in lake-filled peatlands.

Runoff or streamflow from either ombrotrophic or minerotrophic peatlands is directly related to the height of the water table (Figure 4). Greater discharges occur at high water levels for several reasons. First, soil moisture storage capacity is reduced when the water table is high resulting in a higher percentage of runoff for a given precipitation event. Secondly, increased water levels may create greater hydraulic gradients which lead to increased flow. Finally, higher water tables lie in the least decomposed surface peats which exhibit greater hydraulic conductivities and more rapid water movement.

The seasonal fluctuation of water levels differ between ombrotrophic bogs and minerotrophic fens because of the regional groundwater influence

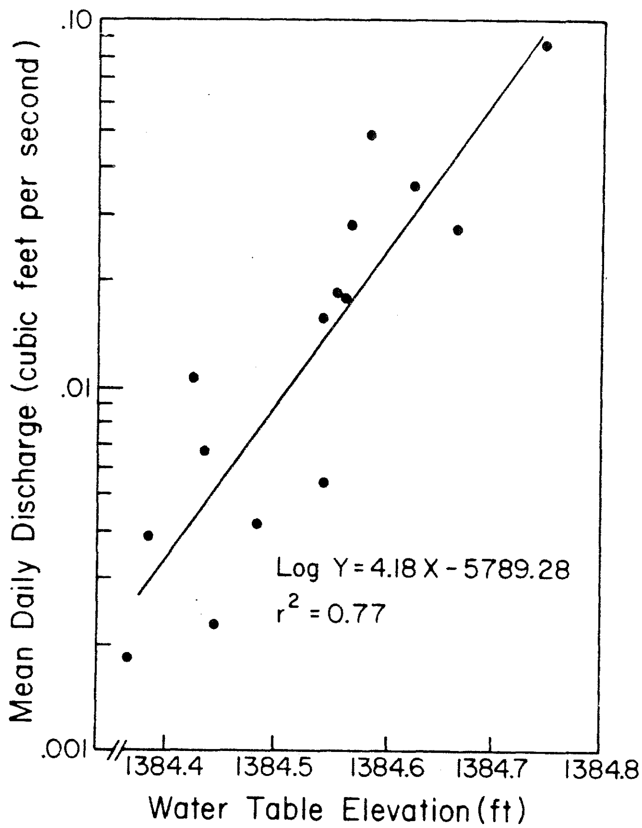

Figure 4. The relation of mean daily discharge to water table elevation for a northern Minnesota bog. (From Bay, 1968.)

in the fen. These differences will be examined in more detail in the following section.

Ombrotrophic Bogs

The annual distribution of runoff from perched bogs in Minnesota has been described by Bay (1968, 1969) and Verry and Boelter (1975). The runoff from the beginning of snowmelt in late March to June 1 represents about two-thirds of the annual water yield. As soils become saturated in the spring due to snowmelt and rain, water tables rise and additional inputs of water contribute directly to runoff; for this reason spring streamflow generally represents the annual maximum.

The increase in net radiation and physiological activity of plants in early summer augment evapotranspiration losses. This increase in evapotranspiration causes reduced water levels and water yield during the summer even though precipitation inputs may be quite large. Researchers in Minnesota and Finland have observed on both perched bogs and extensive built-up peatlands that as water levels recede, streamflow may actually cease during the later part of summer (Heinselman, 1963; Bay, 1968; Heikurainen, 1976). As water levels approach the outlet elevation of the watershed, the hydraulic gradient is reduced. Also, the water flows through deeper peats of greater decomposition, higher bulk densities, and lower hydraulic conductivities which result in lower flow rates. After the water table has reached the level at which streamflow ceases it can be lowered further only by evapotranspiration (Bay, 1969).

In the fall, evapotranspiration is reduced as radiant energy influx declines and vegetation becomes dormant. Precipitation is generally low at this time and likely satisfies soil moisture deficits caused by summer evapotranspiration (Bay, 1969). The flow from bogs may cease in winter as outlets freeze solid (Mustonen, 1964; Bay, 1968).

Contrary to the popular myth, bogs do not regulate the annual distribution of flow by holding water and then releasing it during dry periods (Vidal, 1960; Bay, 1969; Heikurainen, 1971; Boelter and Verry, 1977). However, short-term regulation of snowmelt and stormflows takes place as runoff is delayed by the peatland's relatively flat topography and short-term detention storage (Boelter and Verry, 1977).

Minerotrophic Fens

The water balance of fens has not been studied as thoroughly as that of perched bogs largely because of the difficulty in measuring the quantity of groundwater flowing into and out of the peatland. Fens act as a discharge point for the regional groundwater system and receive a more constant supply of water than ombrotrophic bogs. This results in a more uniform seasonal distribution of streamflow which behaves as the regional groundwater system (Boelter and Verry, 1977).

Peak discharge from a fen in northern Minnesota occurred in the spring and early summer (Verry and Boelter, 1975). This peak flow period was followed by a gradual decrease in flow for the remainder of the year. Even though a less variable flow pattern is observed with fens as compared to perched bogs, they do not store and release water over long periods of time. Fens may provide short-term regulation similar to bogs.

Water Quality Characteristics

The characteristics of peatland water are determined by the chemistry of precipitation and groundwater entering the system and by the chemistry of the peat material. Precipitation and groundwater chemical characteristics reflect the type and quantity of particulate and soluble materials within the atmosphere and substrate, respectively. Groundwater generally contains higher concentrations of dissolved minerals than precipitation (Boelter and Verry, 1977). Calcium is a dissolved mineral of particular interest. Combined with carbonic acid from rainfall, calcium bicarbonate is formed. Calcium bicarbonate may then dissociate to bicarbonate ions which influence pH and determine the buffering capacity of hydrologic systems. Calcium and bicarbonate concentrations are much greater for groundwater than for precipitation. (Boelter and Verry, 1977). As they flow through peat material, the chemistry of both precipitation and groundwater are influenced by the chemical characteristics of the peat. For example, sphagnum peats are generally acidic and promote acidic waters (pH 3 to 4) through cation exchange (Boelter and Verry, 1977). The pH of water affects the solubility and therefore the concentration of many minerals.

The chemical composition of waters from ombrotrophic bogs and minerotrophic fens are quite different (Table 2). Verry's (1975) study reports values for several perched bogs and a minerotrophic fen, all lake-filled peatlands located in northern Minnesota. Data from Heinselman (1970) were collected from several ombrotrophic bog and minerotrophic fen areas within the extensive and built-up Glacial Lake Agassiz peatlands. Studies

Table 2. Composition of Peatland Waters.

	Verry, 1975		Walmsley and Lavkulich, 1975			Gorham, 1956a			Chapman, 1965	Heinselman 1970	
	Bog (average)	Fen	Bog	Transition	Fen	Bog	Transition	Fen	Bog	Bog	Fen
color	445 ± 208 303 ± 120 color units	100± 64 color units				+ = dark - = light ++ to +++	- to ++	- to ++			
pH	3.6 ± 0.3	6.5 ± 0.28	4.2 - 5.9	4.3 - 7.4	6.7 - 7.2	3.67 - 4.30	4.14 - 6.86	6.10 - 7.65	3.2 - 5.4	3.3 - 3.6	5.2 - 6.0
conductivity	spec. cond. 51 ± 13	spec. cond. 125 ± 48	µmho/cm 27-32	µmho/cm 22 - 305	µmho/cm 22 - 305	Kcorr 54 - 89	Kcorr 45 - 79	Kcorr 43 - 119	Kcorr 49 - 64		
Total acidity (as $CaCO_3$)	48.2 ± 24 (mg/l)										
Total alkalinity (as $CaCo_3$)		54.2 ± 28.0									
Total - N	1.34 ± 0.64	0.58 ± 0.29									
Organic - N	0.69 ± 0.04	0.33 ± 0.22									
Ammonia - N	0.45 ± 0.39	0.15 ± 0.14									
Nitrate - N	0.20 ± 0.25	0.10 ± 0.07	ppm 1.2 - 1.6	ppm 1.9 - 7.9	ppm 6.2 - 9.6						
Nitrate - N	0.003 ± 0.003	0.003 ± 0.003									
Total - P (as PO_4)	0.19 ± 0.18	0.09 ± 0.04									
Cl	0.7 ± 0.8	0.4 ± 0.4	ppm 1.4 - 2.0	ppm 1.6 - 6.8	ppm 3.6 - 6.7						
SO_4	4.6 ± 2.2	6.0 ± 4.2									
Fe	1.35 ± 0.8	0.98 ± 0.48									
Ca	2.4 ± 1.0	16.6 ± 9.0	ppm 0.8 - 1.0	ppm 1.6 - 41.0	ppm 25.8 - 43.0	mg/l 1.3 - 1.8	mg/l 2.1 - 7.3	mg/l 2.3 - 17.5	meq/l 0.05 - 0.19	ppm 1.8 - 2.6	ppm 2.6 - 6.4
Na	0.6 ± 0.3	2.0 ± 1.0	ppm 0.2 - 1.7	ppm 0.4 - 2.8	ppm 2.0 - 2.1	mg/l 4.5 - 9.6	mg/l 3.5 - 6.3	mg/l 3.6 - 6.0	meq/l 0.21 - 0.26		
Mg	0.97 ± 0.36	2.88 ± 0.93	ppm 0.3 - 0.6	ppm 0.3 - 14.3	ppm 12.7 - 20.0				meq/l 0.09 - 0.30	ppm 0.0 - 0.3	ppm 0.4 - 4.7
Mn	0.06 ± 0.05	0.08 ± 0.06									
K	1.3 ± 0.6	1.1 ± 0.4	ppm 0.3 - 0.6	ppm 0.4 - 3.9	ppm 2.6 - 3.7	mg/l 0.2 - 2.0	mg/l 0.12 - 1.52	mg/l 0.17 - 1.75	meq/l 0.01 - 0.05		
Al	0.79 ± 0.43	0.16 ± 0.06									
Cu	0.04 ± 0.07	0.18 ± 0.36									
Pb	<0.05	<0.05									
Zn	0.08 ± 0.11	0.11 ± 0.17									
Si	2.7 ± 2.1	4.9 ± 4.0	ppm 0 - 2	ppm 0 - 6	ppm 6 - 8						
O_2			ppm 5.1 - 7.8	ppm 0.8 - 6.3	ppm 0.7 - 3.9						
F			ppm 0	ppm 0 - 1.3	ppm 0.3 - 1.4						
HCO_3	meq/l 0.0000	meq/l 0.5415				mg/l 0.0	mg/l 0.0 - 14.9	mg/l 6.6 - 71.4			

by Walmsley and Lavkulich (1975) and Gorham (1956a) represent bog, fen, and transition areas in Canada and Britain, respectively. Chapman's (1965) bog study was also done in Britain.

Ombrotrophic Bogs

Bog waters exhibit low conductivity, low pH, and high color values as compared to fens (Table 2). Low conductivity indicates low concentrations of dissolved mineral ions. The ions in bog waters are obtained almost exclusively from atmospheric precipitation (Gorham, 1956b). The low pH and high color values, on the other hand, result from contact with the organic soil. In addition to cation exchange stated earlier, acidity may also be influenced by anaerobically produced hydrogen sulfide which diffuses to bog pools where it is oxidized to sulfuric acid (Gorham, 1956b). High color values of bog waters appear to be caused by humate or iron-humate compounds derived from decomposing organic material (Steelink, 1977).

Verry's (1975) results show that concentrations of total N, organic N, ammonia N, nitrate N, total P, Cl, Fe, K, and Al were greater in streamflow from perched bogs than from the fen. Color, specific conductance, total N, total P, chloride, total Fe, Ca, Na, Mg, Mn, Al, Zn, and Si were inversely related to streamflow rate in perched bogs.

Minerotrophic Fens

While the perched bogs in Verry's (1975) study exhibited higher concentrations of organically derived ions, the fen water had higher concentrations of mineral ions such as Ca, Na, Mg, Mn, Cu, Zn, Si, and sulfate due to groundwater inflow. The inflow of calcium bicarbonate accounts for the near neutral pH of fen water (Gorham, 1956a; Verry, 1975). Since the solubility and concentration of Fe and Al are inversely influenced by pH, the higher pH of fens results in their reduced concentrations.

Some discrepancy exists in describing the relationship between the concentration of fen water constituents and flow rate. Verry (1975) found no significant relationship between concentrations and streamflow rate although nutrient concentrations and specific conductance were reduced at peak snowmelt. Conversely, Sparling (1966) related water characteristics to flow rate at 54 sites within a number of Canadian fens and reported that pH and oxygen concentration are higher at greater flow rates while ferrous iron, soluble manganese, and sulfide exhibit greater concentrations at low flow rates due to the lower oxygen concentration. Aluminum concentration is highest at low flow rates due to lower pH values.

Table 2 shows that the studies by Verry (1975), Gorham (1956a), and Walmsley and Lavkulich (1975) generally agree in comparing the relative differences in nutrient concentrations between bog and fen waters, however, some differences exist. Gorham (1956a) found a higher concentration of sodium in bog waters as compared to fen waters but these areas were near the coast and were likely influenced by sea spray. Walmsley and Lavkulich (1975) found potassium concentrations to be greater in fen than in bog waters which contradicts the findings of Verry (1975) and Gorham (1956a). A similar disagreement over chloride and nitrate-N concentrations exists between Verry (1975) and Walmsley and Lavkulich (1975). The reason for these differences is unknown.

In examining nutrient concentrations weighted by flow rate for bogs and fens, Verry (1975) concluded that:

> "Weighted concentrations for the two watershed types are similar for organically derived ions (total P, total N, and total Fe) and for chloride. In general, nearly equal amounts of organically derived nutrients are leached from both watershed types in an equal volume of water leaving the watershed as streamflow. Total yield (kilogram/year) of all chemical constituents is primarily a function of the annual volume of streamflow."

METHODS OF HARVESTING PEAT

Early methods of peat extraction in Europe consisted of hand removal of peat for domestic fuel. With the increased cost of manual labor and improved technology in the early 1900's, mechanical harvesting of peat evolved as the only economical means of large-scale peat extraction.

The initial task to be completed with any peat harvesting operation is a survey of the natural peatland. Depending upon the harvesting procedure, peatland drainage may then be required. Drainage is required for the peat surface to support large-scale harvesting machinery required by some methods (Korchunov et al., 1976; MacDougall and Richards, 1948). Those methods which require drainage include (1) sod peat, (2) milled peat and (3) shaved peat. The hydraulic dredge, hydro-jet and dragline excavation methods will also be briefly discussed.

Sod Peat

The sod peat method of harvesting is generally used when the peat is to be used for energy production.[4] Drainage ditches are placed approximately 27m apart and surface vegetation and moss are removed (MRI, 1976). The peat is then excavated, macerated, formed, extruded, and cut into blocks. The blocks are turned and dried on the field eventually to be collected, stacked, and stockpiled. As the harvesting operation removes a layer of peat (3-4 m) the ditches may be dug deeper to facilitate drainage.

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[4] R. S. Farnham. 1978. Personal communication.

Milled Peat

Milled Peat may be used for either horticultural or energy purposes. The harvesting area is drained with ditches spaced 15-45 m apart (MRI, 1976). After drainage the surface is cleared of vegetation and approximately 5-8 cm of peat is prepared for milling on the cleaned and cambered surface.[5] The milled peat is allowed to dry which is improved by rototilling, discing, and harrowing. When dried (45-55 percent moisture on a volume basis) approximately 1.3 cm is scraped or graded into ridges or windrows and conveyed to stockpiles for transport to packaging plants (MacDougall and Richards, 1948; Plummer, 1949). Milled peat may also be vacuum harvested (Brower, 1966).

Shaved Peat

This method is frequently used for horticultural peat extraction. After clearing and draining the peat is disced and bulldozers are used to "shave" the upper layer of peat into windrows. Front-end loaders are used to remove the windrowed peat.

Peat harvesting methods which do not require drainage are:

1. Hydraulic dredge
2. Hydro-jet
3. Dragline excavation

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5 Ibid.

Hydraulic Dredge

The hydraulic dredge is used in British Columbia for harvesting horticultural peat although it may also be used to harvest peat for energy purposes.[6] Initially a pond or floatation area is formed by dredging a small area of peat. A floating platform or hovercraft loaded with dredging equipment is placed in the pond and proceeds to excavate peat by two methods. A surface clamshell type dredge excavates the upper meter of peat which is dumped into a separator that screens and discards the roots and wood within the peat. At the same time a subsurface cutter-head dredge augers materials from approximately a one to two meter depth. Pumps transfer the peat mixture (from both clamshell and cutter-head dredge) through a pipeline to a plant which mechanically dewaters the peat. Dewatering consists of reducing the moisture content of the peat by passing the slurry through a paper mill roller press. The moisture content of the peat is further reduced by passing it through artificial dryers. The extricated water is pumped back to the harvesting pond or released to a ditch near the plant.

Hydro-jet

As described by MacDougall and Richards (1948), this method uses water jets mounted on top of a floating platform to wash peat from the bog. The jets of water wash peat away from roots and debris. The peat pulp formed by this method is then pumped and spread in about an 8 inch

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6 Ibid.

layer on a drained field. The removal of excess water from the pulp may be facilitated if the drainage field has a convex surface. After several days of drying, the pulp becomes a plastic mass which is cut into blocks for further drying. If a mechanical means of removing the excess water is used as with hydraulic dredging, the ditched spreading ground is not needed.

Dragline Excavation

A dragline or other bucket type excavator is used to excavate the peat with this method. The peat is then put into a slurry and dried in the same way as hydraulic dredge and hydro-jet peat.

HYDROLOGIC CONSEQUENCES OF PEAT HARVESTING

Little information exists concerning the hydrologic effects of peat harvesting. The information that is available is often conflicting. For example, milled peat harvesting to a final thickness of 0.5m in the USSR has not adversely affected the subsequent use of the peatland for parks, forestry, hunting grounds, of fisheries (Korchunov et al., 1976). Yet, in Poland, peat harvesting and associated drainage reportedly had detrimental impacts on the peatland and the surrounding region (Olkowski and Olesinski, 1976). The following discussion examines possible impacts of peat harvesting on both water quantity and quality.

Impacts on Water Yield

The impacts of peat harvesting on water yield characteristics depend upon: (1) the impact on the immediate harvest area, (2) location of the harvest site within the watershed and with respect to outflow points, and (3) size of the harvested area in relation to the size of the watershed. The effect of harvesting on the immediate harvest area is of primary concern in this discussion, and must be determined before the total impact can be assessed. Harvesting effects on water yield may be different for drained and undrained methods.

Drained Methods

The hydrologic effects on the immediate harvest area may be estimated by examining the impacts associated with the harvesting process.

This process consists of (1) the removal of surface vegetation, (2) drainage, and (3) peat extraction.

Removal of Vegetation

The amount of evapotranspiration from peatlands greatly influences the quantity of streamflow, particularly during the summer. Vegetation removal will reduce transpiration in proportion to the amount of vegetation removed. Reduced transpiration may in turn diminish the rate at which groundwater levels drop in late summer. Also, diminished available storage in the peatland would enhance rainfall-runoff efficiency in the summer. Conversely, evaporation from the soil surface may increase due to the increase in solar radiation reaching the soil surface (Kittredge, 1948). Evaporation may also increase due to a steepening of the vapor pressure gradient associated with increased wind velocity and duration due to forest overstory removal (Brown, 1972). The albedo or reflectivity of the active evaporating surface could also be reduced because of the change from green vegetation to the exposed, dark organic soils. The result would be increased net radiation available for evaporation. The balance between reduced transpiration and increased evaporation will determine whether runoff increases or decreases due to vegetation removal. It is expected, however, that the decrease in transpiration will exceed the increase in evaporation, leading to increased runoff.

Another impact of vegetation removal is the reduction in interception loss. Vegetation is capable of intercepting snow and rainfall before it reaches the ground. Water which is trapped in this fashion evaporates to the atmosphere (Heikurainen, 1971). The impact of reduced interception loss is to increase the amount of precipitation which reaches the soil surface and thereby increase runoff.

The removal of forest stands may influence the timing of spring snowmelt. Forest cover delays snowmelt, resulting in lower flood peaks of longer duration (Heikurainen, 1975). Also, the greater the stand density the greater the delay (Heikurainen, 1976). Therefore, increased spring-flood flows might be expected if large areas were converted from forest to "open" conditions.

Vegetation removal may also influence the type and depth of frost, which affects spring snowmelt infiltration. The influence of frost on infiltration may be particularly apparent in heavy textured soils (Post and Dreibelis, 1942; Storey, 1955). Concrete frost, a type which creates impermable conditions, is most prevalent in bare soils and open areas where the depth of frost is often greatest. The removal of vegetation, therefore, may cause deeper frost penetration and more extensive concrete frost (Weitzman and Bay, 1963). Reduced infiltration, increased surface runoff,[7] and increased spring peak flows could result, especially in denser hemic and sapric peats.

Vegetation removal by scraping off the live surface mosses changes the micro-relief, resulting in a more uniform, smooth surface. A reduction in depression storage and an increase in "surface" runoff is

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[7] Surface runoff is used here to denote quick-flow runoff, which may in some cases physically occur in the upper few centimeters of the soil profile depending on soil porosity and the openness at the surface.

likely to result. The overall impact of vegetation removal may be an increase in maximum discharge and total water yield from the immediate harvest area.

Effects of Drainage

The second impact on the immediate harvest area to examine is that associated with peatland drainage. Drainage represents one of the greatest potential impacts associated with peat harvesting. Drainage causes a lowering of the water table in the peatland (Lavrov et al., 1975, Olkowski and Olesinski, 1976). On a volume basis natural peatlands generally have water contents of 90-95 percent while drained peat soils exhibit moisture contents of approximately 80 percent (Heikurainen, 1964; Korchunov et al., 1976). The lowering of the water table and the related drop in moisture content change the physical properties of the organic soil and the peatland topography through the process of subsidence.

The subsidence of peatlands is due to shrinkage, oxidation, compression, and compaction (Morris, 1949; van der Molen, 1975; Schothorst, 1976). Shrinkage of peat occurs due to moisture loss. As the moisture content is lowered, soil aeration improves and this stimulates the oxidation or decomposition of organic matter by micro-organisms. Decomposition in drained peatlands occurs throughout the summer due to drier surface conditions while natural peatlands undergo decomposition only in the late summer (Kozlovskaya, 1963). Compression occurs due to the loss of the bouyant force of water with an increased force exerted by the drained peat layer of 62.4 lbs/ft^2 for each foot of drop in the water table or equally 1 g/cm^2 for each cm of drop in the water table (Morris, 1949; Schothorst, 1976). Heavy machinery causes some peat compaction. This compaction, however, is probably temporary and will not result in permanent compaction (Morris, 1949).

The amount of subsidence which occurs following drainage depends primarily upon peat type and intensity of drainage (Malmstrom, 1928; Robertson, 1933; Prus-Chacinski and Harris, 1963). Undecomposed, loose peat exhibits greater subsidence than decomposed, dense peat (Malmstrom, 1928; Robertson, 1933; Nesterenko, 1976). Walmsley and Lavkulich (1975) have shown bog peats are less decomposed than peats from fens. Therefore, bogs may be expected to exhibit greater subsidence following drainage than fens.

The intensity of drainage, determined by both ditch spacing and depth, is important because it establishes the height of the water table and thus the amount of subsidence. The water table is lowest at the ditch and increases in height with distance from the ditch (Figure 5). Therefore, the shorter the distance between ditches, the lower the water table. This is supported by Ferda and Novak (1976) in Czechoslovakia where ditches placed 30, 60, and 100m apart produced average depths to the water table of 75, 50, and 35cm, respectively. The depth of ditches also influence water table levels (Figure 5). Lowering the water level in the ditch, assuming the outlet is lowered, will lower water tables in the peatland, promoting greater subsidence.

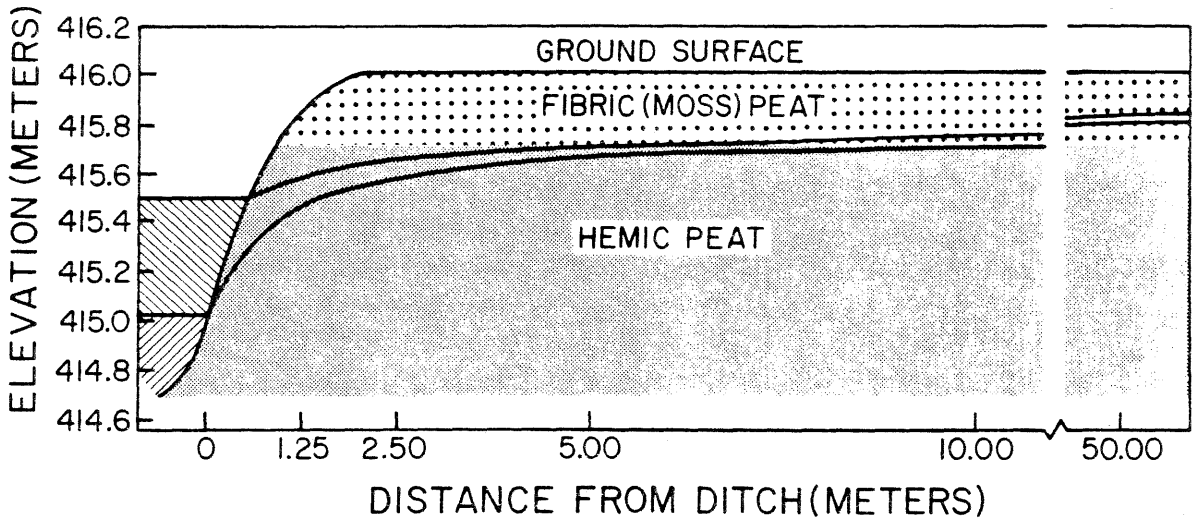


Figure 5. Influence of ditch water level on peatland water table elevation. (From Boelter, 1972.)

Subsidence results in changes in the physical and hydraulic properties of peat (Figure 6). The rate of peatland subsidence and the changes in the physical and hydraulic properties are greatest immediately following drainage and decrease with time. Macropore space and permeability decrease as bulk density increases (Eggelsmann, 1975; Baden, 1976; Nesterenko, 1976). The decomposition of peat fiber reduces macropore space but also can cause blockage of soil pores by micro-organisms and their products (Doering, 1965; Walmsley and Lavkulich, 1975). Increased bulk density would be expected to reduce hydraulic conductivity and the saturated infiltration rate and increase water retention. Surface runoff and peak discharge may then increase for given storms, over that which would occur from undisturbed areas.

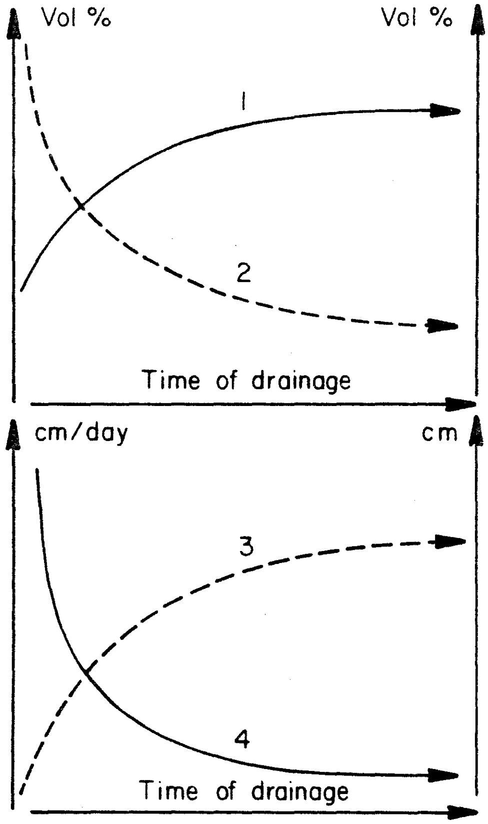


Figure 6. Changes in the physical properties of peat with time as a result of peatland drainage. 1) Bulk density, 2) Macro-pore space, 3) Subsidence, 4) Permeability. (From Eggelsmann, 1975.)

The overdrainage of organic soils can create different changes in physical and hydraulic properties. Overdrainage occurs when peat becomes air dry (below approximately 30 percent moisture content on a volume basis) and exhibits a granular, crumbled surface with hydrophobic characteristics (Robertson, 1933; Boelter, 1966; Olkowski and Olesinski, 1976). Reduced infiltration and increased surface runoff results (Tallis, 1973).

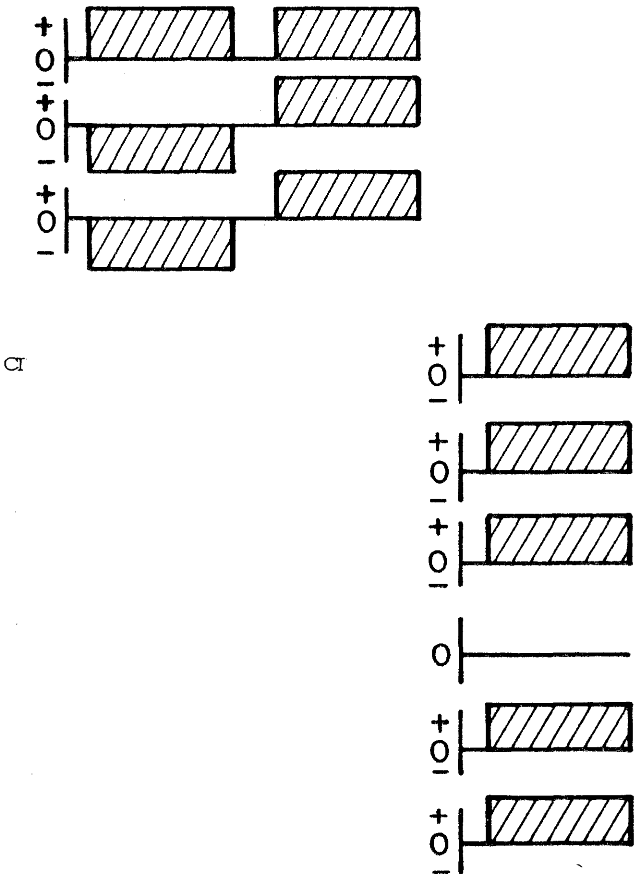
In addition to changing physical properties, subsidence also changes the surface topography. Subsidence is greatest near the ditch creating a convex surface between parallel ditches (Malstrom, 1928; Heikurainen, 1957; Baden, 1976). This facilitates surface runoff and could lead to increased surface runoff and peak flows.

The changes in water level, physical properties, and topography of peatlands due to drainage alter both discharge rate and volume (Figure 7). Maximum discharge for spring and summer, may increase or decrease. Increased maximum discharge could be attributed to the reduced time of concentration of runoff caused by ditching and areas of compaction and subsidence. Huikari et al. (1966) reported that increasing ditch depth in Finland augmented maximum discharge. Also closely spaced ditches tended to increase peak flows. Research by Ferda and Novak (1976) supports this conclusion; ditch spacing of 30m produced an increase in maximum discharges following snowmelt and rainfall events compared to an undisturbed bog, but spacings of 60 and 100m resulted in decreased peak flow (Figure 7). More intensive drainage results in greater subsidence, reduced infiltration rate, and increased convexity which promotes surface runoff. Maximum discharge may, however, decrease if substantial storage were created by the lowering of the water table.

Minimum discharge from bogs has been reported to increase as a result of drainage (Figure 7). Such increases may be attributed to several factors. Lower water table elevations tend to reduce evapotranspiration losses which are particularly evident during the summer minimum flow period. With reduced evapotranspiration more water is available for runoff. Though the hydraulic gradient, which provides the driving force for

Figure 7. Impacts of peatland drainage on the discharge characteristics of the immediate drainage site (overstory undisturbed).

Peatland Type	Ditch Spacing	Ditch Depth	Maximum[5]	Minimum[5]	May to October[6] Water Yield
Bog	30m				
	60				
	100				
Bog	5m	30 cm			
	10	30			
	20	30			
	100	30			
	30	46			
	60	77			



(+) = increase
(0) = no change
(-) = decrease
5 Ferda and Novak (1976) - Czechoslovakia
6 Huikari et al (1966) - Finland

water movement, is increased as ditches increase the head over the length of flow, movement of subsurface water is slowed by flow through deeper denser peats. The combination of increased available water during the low flow period and the slower movement of that water results in increased minimum discharge. Conversely, if water yields during high flow periods are increased significantly, less water may be available for sustaining low flow during late summer periods.

Minimum flows from fens may also be influenced by drainage. Using a water budget approach, Hommik and Madissoon (1975) reported increased groundwater inflow following drainage of a fen. Such an increase in groundwater inflow would tend to increase minimum discharge, although the cause of the increase was not explained. As evident from this discussion, some uncertainty exists concerning drainage effects on low flows from bogs and fens.

Total water yield from a harvest site would likely increase, depending primarily upon the intensity of drainage. The lowering of the water table apparently explains reductions in evapotranspiration (Ivitskii, 1938, Klyueva, 1959; Heikurainen, 1964; Mustonen, 1964; Paivanen, 1974; Bulavko and Drozd, 1975). May to October water yield in Finland was significantly increased with ditch spacing under 20m as compared to 100m spacing (Figure 7). Water yield also increased with deeper ditches.

Table 3 summarizes the results of several studies on the impacts of drainage on the discharge characteristics of peatland watersheds. Due to the absence of information in these studies concerning peatland type,

Table 3. Summary of drainage impacts on the discharge of peatlands.

Peatland Type	Peat Type	Basin Area	% Drained	Discharge change: spring	summer	fall	winter	max	min	Total Annual	Author and Country
?	?	?	6-25		(+)		(+)			(-) or (+)	Bulovko and Drozd, 1975, USSR
Bog	?	?	?	(-)	(+)			(-)			Heikurainen, 1976 Finland
?	?	67-8770 km^2	5-25	(-)	(+)	(+)	(+)	(-)	(+)	(+)	Klueva, 1975, USSR
?	?	?	?	(-)	(+)		(+)			(0)	Klyueva, 1959, USSR
Open, watery sedge bog	?	?	?					(-)			Mustonen, 1964, Finland
Raised bog	?	533 ha	40					(+)	(+)	(+)	Mustonen, 1964, Finland
Open bog	?	5 km^2	40		(+)			(+)	(+)	(+)	Mustonen and Seuna, 1975 Finland
Bog	Moss	?	?		(+)			(+)			Vidal, 1960, Germany

(+) = increase
(0) = no change
(-) = decrease
? = information not available

drainage intensity, size of drained area, size of the watershed, and location of the area within the watershed, specific conclusions cannot be drawn. Variations in the findings of these studies may be attributed to differences in the above characteristics.

Peat Extraction

After considering vegetation removal and drainage, the hydrologic effects of peat extraction need to be examined. As peat is harvested, the least decomposed soil is removed first. As harvesting progresses, the exposed bog surface exhibits greater decomposition and bulk density. The new peatland surface would thus have lower infiltration rates, leading to increased surface runoff and maximum discharges. Also the available storage of the system is reduced because the more decomposed peats retain more water. If large enough areas are affected, it is conceivable that natural recharge of the groundwater may be reduced resulting in reduced average and minimum flows.

The magnitude of impacts on maximum and minimum discharge due to peat extraction will probably depend upon the relative differences between physical properties of the undisturbed surface peat and the underlying peat. The greatest impact could be observed when loose, fibric surface peat, underlain by dense, sapric peat, is extracted. The impact may be less if moderately decomposed surface peat were extracted and the underlying peat exhibited similar density and degree of decomposition.

The expected combined impacts of vegetation removal, drainage, and peat extraction on water yield characteristics of the harvest site are summarized in Table 4. Maximum discharge and total water yield may increase for the reasons shown. The impact of peat harvesting on minimum discharge, however, is uncertain. If evapotranspiration reductions exceed the increased runoff caused by lower infiltration and hydraulic conductivity and lower available storage, minimum discharges may increase. If groundwater recharge is reduced more than evapotranspiration losses, then minimum discharge should decrease.

The location of the harvest site within the total watershed influences the overall impacts on water yield characteristics of the watershed. Wisler and Brater (1959) state that increased peak discharge from the drainage site may result in increased or decreased peak discharges from the watershed, if the drained area lies near the headwaters or the bottom of the basin, respectively. If the drainage site lies in the headwaters, the accelerated discharge from the site will cause a reduction in the time of concentration and an increase in maximum discharge. However, if the drainage site is not extensive and is located near the outflow point of the basin, maximum discharge may be reduced, because the accelerated discharge from the lower basin leaves the watershed before the upstream water arrives. Location of the harvest site within the watershed is not expected to be important in determining the influence of harvest site impacts on minimum discharge and total water yield of the watershed.

The size of the harvest area in relation to the total watershed area, however, is expected to influence maximum discharge, minimum discharge, and total water yield of the watershed. In general, the larger

Table 4. Expected Impacts of Drained Peat Harvesting Methods on Harvest Site Water Yield Characteristics.

Maximum Discharge (spring and summer) - Increase

Due to: Vegetation removal

- reduction in depression storage
- elimination of interception loss
- reduced infiltration associated with increased frost*
- accelerated snowmelt*

Drainage

- accelerating effect of ditches
- possible increase in peatland surface convexity
- reduced infiltration due to subsidence

Peat Extraction

- reduced infiltration

Minimum Discharge - Uncertain

Total Water Yield - Increase

Vegetation removal

- reduced transpiration
- reduced interception loss

Drainage

- reduced evaporation

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* Frost and snowmelt should not affect summer maximum discharge.

the harvested area, the greater the influence on the discharge characteristics of the watershed.

Undrained Methods

Peat harvesting without drainage results in pond formation which may have hydrologic impacts different from drained methods. Peat extraction results in reduced interception losses and increased available storage within the basin created by extraction. As subsurface flow from the surrounding peat fills the basin, the available moisture storage in the peat surrounding the pond may increase. Evaporation from the pond may exceed evapotranspiration losses from the previously undisturbed peatland (Romanov, 1962). Also, peat extraction will reduce the peatland microrelief and depression storage which affects the timing of runoff events.

The above impacts become particularly important if an outlet, either natural or artifical, drains the harvesting pond. If an outlet exists, maximum discharge from the harvest site may increase due to the quicker outflow response of a free water surface as compared to the original peatland. This may be particularly true when extraction is halted or completed with no further increase in storage. A decrease in minimum discharge from the harvest site may also be attributed to the quicker runoff response. Minimum flow and total water yield may be decreased if evaporation rates increase. Differences between peatland evapotranspiration and free-water evaporation cannot be estimated without further experimentation.

If no outlet exists, the impacts of undrained peat harvesting may be diminished as discharge will probably occur through the surrounding peat, similar to the undisturbed peatland. Maximum discharge from the harvest site may not be significantly changed. However, minimum flow and total water yield from the harvest site would be reduced if evaporation losses increased.

The impacts of undrained peat harvesting (with outlets) on watershed discharge characteristics, like drained harvesting methods, may also depend upon location of the harvest site. If located near the headwaters of the watershed, the harvest site may increase maximum discharges from the watershed. If the harvest site is not extensive and if located near the bottom of the basin, a decrease in maximum flow from the watershed may occur.

For watersheds which contain harvest ponds (without outlets), the impacts on watershed discharge may be minimal. Maximum discharge is not expected to change signignificantly due to pond outflow, which must flow through peat material. Minimum discharge and total water yield, however, are expected to decrease if evaporation increases; the magnitude of decrease depends on the size of the harvest area.

Impacts on Water Quality Characteristics

Water quality impacts, like those of water yield, may depend upon the method of harvesting. Again, impacts will be discussed from the viewpoint of drained and undrained methods.

Drained Methods

The majority of impacts on water quality due to drained methods of peat harvesting may be attributed to drainage itself. Drainage may promote changes in water quality due to ditch construction, increased microbial activity, and possible peat erosion. Heikurainen (1971) suggests that humus content of discharge waters could be increased during ditch construction as a result of peat disturbance. Drainage may also affect water quality by encouraging decomposition which could release organically bound nutrients (Kuntze, 1976). Research by Largin et al., (1976) reported that the concentration of organic and mineral substances increased following drainage and harvesting of an ombrotrophic peatland. A slight increase in pH was also observed. Because decomposition is not a fast process, changes in water quality due to nutrient release may be small during the harvesting operation. Upon completion of peat extraction, however, the impact on water quality could increase with time (Largin et al., 1976).

The possibility of reduced water quality due to peat erosion also exists. Peat erosion requires the exposure of bare peat and the incision by surface flow (Tallis, 1973). Peat harvesting provides the bare surface through vegetation removal and extraction, while drainage, particularly overdrainage, may produce cracks in the peat surface which could initiate incision.

The amount of erosion may depend on the type of peat that is exposed. Korpijaakko and Pheeney (1976) report that undecomposed sphagnum peat may resist erosion due to its high fiber content. Hemic and sapric peats would therefore, be expected to have a greater potential for peat erosion.

If drainage ditches react like erosion gullies, increased contributions of organic material to receiving waters may be expected. The erosion of peat from gullies occurs by two methods: (1) freezing and subsequent thawing of the gully sides which loosens peat making it more susceptible to removal by rainfall; (2) the gully floor shrinks and cracks when dry and then is eroded when flow resumes (Tallis, 1973). Futhermore, flow rates exceeding 40-50 l/min. (.02 - .03 cfs) tend to increase erosion considerably by scouring the gully sides (Tallis, 1973). Whether ditch floors become completely dry and erode, like gully floors seems unlikely. However, ditch sides may freeze, thaw, and erode analogous to gully sides.

Milled peat and possibly shaved peat harvesting methods may exhibit an impact on water quality not attributable to the sod method of harvesting. Milled and shaved peat may be more subject to wind transport to ditches and nearby water bodies than sod peat. Additions of organic matter and subsequent decomposition in receiving waters could affect the nutrient budgets and eutrophication of receiving waters. Discharged peat material carries with it phosphorus and nitrogen (Crisp, 1966). However, an increase in humus content may decrease biomass production by restricting the penetration of solar radiation (Heikurainen, 1975). To complicate the situation, humic and fulvic acids, released by decomposition, may either stimulate or restrict the growth of aquatic organisms (Steelink, 1977). Therefore, the impacts on eutrophication are uncertain.

An increase in trophic status may result from the increase in organically bound nutrients contributed by decomposition within the harvest site. The addition of these nutrients would be greatest following harvesting and may increase as long as adequate drainage and aeration is provided.

The addition of peat material could also increase biological oxygen demand and result in diminished oxygen concentrations. Although humic and fulvic acids resist biological decomposition, the utilization of other organic substances by micro-organisms may reduce oxygen concentrations in receiving waters.

A slight increase in pH of discharge waters may also occur as a result of drainage, particularly, if ditches intersect mineral soil. The acidic bog waters may be neutralized by bicarbonate ions within the substrate which could promote a more productive aquatic environment.

Undrained Methods

Within the harvest pond, a number of impacts on water quality may occur. The disturbance of peat by undrained harvesting methods along with the returning extricated water from the drying plant may increase suspended peat material. Some of this organic matter will likely settle within the harvesting pond. Water from the drying plant may also contain increased quantitites of dissolved organic compounds and nutrients due to disruption of the peat by the roller presses. Research is needed to determine if this impact actually exists.

Harvesting ponds which possess outlets may have a greater impact on the quality of receiving waters than harvesting ponds without outlets. If an outlet exists, water imparted with the above characteristics may move with little restriction into receiving waters. However, if no outlet exists, the pond discharge will likely flow through surrounding peat material which could act as a filtering mechanism for suspended solids and also allow possible utilization of dissolved organic compounds by bog vegetation before contributing to streamflow. The impacts on receiving waters due to increased additions of organic matter and dissolved organic substances should be similar to those previously described for drained peat harvesting.

CONCLUSIONS

1. Large scale peat harvesting may have the following impacts on water yield and water quality characteristics:

   a. Drained Methods of Peat Harvesting

      (1) Increased maximum discharges during spring and summer.

      (2) Increased total or annual water yield.

      (3) Increased additions of organically derived nutrients, dissolved organic compounds, and organic particulate matter to peatland discharge waters.

   b. Undrained Methods of Peat Harvesting

      (1) Increased maximum discharges, particularly if a harvest pond outlet exists. If an outlet does not exist, little impact on maximum discharge.

      (2) Increased additions of organically derived nutrients and peat particulate matter in peatland discharge waters especially if harvest pond outlets exist or if drying plants release extricated water directly to receiving waters.

2. Impacts of peat harvesting on the water resource are uncertain because of limited hydrologic studies. Research that quantifies water budget components and water quality constituents is sorely needed for undisturbed and harvested peatlands.

RECOMMENDATIONS

1. Based on the limited knowledge and uncertainty of the hydrologic response to widespread harvesting of peat:
    a. Extensive areas in excess of several thousand acres should not be harvested by drainage methods. By providing natural peatland areas interspersed among harvested areas, anticipated effects on peat flows may be diminished. One expansive area of 100,000 acres or more could conceivably result in significant peak flow increases. Studies concerning harvesting effects on peak flow are needed.
    b. The use of downstream control structures should be investigated if large areas are to be drained. Maximum discharge and water quality effects of undrained methods on downstream discharge can be controlled by providing no outlet.
    c. Until water quality effects are understood, discharge into receiving waters from harvested areas should be minimized.
    d. Drying plants should discharge extricated water to the harvest pond or peatland rather than directly to ditches or receiving waters.
2. Research is needed to allow for a reasonable analysis and proper impact assessment on water resources and includes the following:
    a. Hydrologic characterization of natural minerotrophic fens, of the type to be harvested. A water budget analysis would provide evapotranspiration and water yield responses for such areas.

b. Quantification of the following hydrologic processes before and after harvesting:

   1. evapotranspiration losses
   2. summer low-flow discharges
   3. infiltration-subsurface flow relationships
   4. groundwater flow-water table response
   5. soil frost-snowmelt relationships
   6. time of concentration of stormflow events

c. Quantification of changes in water quality indicators before and after harvesting. The magnitude and effects of wind-deposited peat soils on the water quality of adjacent lakes and streams should also be included. Special emphasis should be placed on pH, bicarbonate, calcium, phosphorus and nitrogen. In addition, heavy metal concentrations need to be monitored closely.

d. Monitoring of streamflow and water quality from ongoing or new harvest sites.

e. The development of methodologies or models capable of predicting the effects of different harvesting methods on annual water yield, low-flow, peak discharge and water quality.

REFERENCES

Baden, W. 1976. Influence of human activity on peatlands and surrounding areas. Proc. Fifth Int. Peat Congr., Poznan, Poland. 1976. 1: 191-205.

Bay, R. R. 1968. The hydrology of several peat deposits in northern Minnesota, U.S.A. Proc. Third Int. Peat Congr., Quebec, 1968. pp. 212-218.

________. 1969. Runoff from small peatland watersheds. J. Hydrol., 9: 90-102.

Boelter, D. H. 1964. Water storage characteristics of several peats in situ. Soil Sci. Soc. Amer. Proc. 28: 433-435.

________. 1966. Hydrological characteristics of organic soils in Lake States watersheds. J. Soil and Water Conserv. 21:2:50-53.

________. 1969. Physical properties of peats as related to degree of decomposition. Soil Sci. Soc. Amer. Proc. 33:606-609.

________. 1972. Water table drawdown around an open ditch in organic soils. J. Hydrol., 15:4: 329-340.

Boelter, D. H. and E. S. Verry. 1977. Peatland and water in the northern Lake States. USDA Forest Serv. Gen. Tech. Rep. NC-31, North Cent. For. Exp. Stn., St. Paul, Minnesota. 22 p.

Boffey, P. M. 1975. Energy: plan to use peat as fuel stirs concern in Minnesota. Science. 190: 1066-1070.

Brower, R. M. 1966. A conventional (field harvester) peat operation. State of Minnesota, Department of Iron Range Resources and Rehabilitation. 68 p.

Brown, J. M. 1972. The effect of overstory removal upon surface wind in a black spruce bog. U.S. Forest Service Research Note, North Central Forest Experiment Station. No. NC-137. 2 p.

Bulavko, A. G. and V. V. Drozd. 1975. Bog reclamation and its effect on the water balance of river basins. Int. Symp. on the Hydrol. of Marsh-Ridden Areas, UNESCO, Minsk, 1972. pp. 461-467.

Chapman, S. B. 1965. The ecology of Coom Rigg Moss, Northumberland. III. Some water relations of the bog system. J. Ecol. 53:2: 371-384.

Crisp, D. T. 1966. Input and output of minerals for an area of pennine moorland: The importance of precipitation, drainage, peat erosion and animals. J. Applied Ecol. 3:2:327-348.

Doering, E. J. 1965. Change of permeability with time. Drainage for Efficient Crop Production Conference. 1965. Amer. Soc. of Agr. Eng., St. Joseph, Michigan. pp. 32-36.

Dooge, J. 1975. The water balance of bogs and fens. Int. Symp. on the Hydrol. of Marsh-Ridden Areas, UNESCO, Minsk, 1972. pp. 233-271.

Eggelsmann, R. 1975. Physical effects of drainage in peat soils of the temperate zone and their forecasting. Int. Symp. on the Hydol. of Marsh-Ridden Areas, UNESCO, Minsk, 1972. pp. 69-76.

Ferda, J. and M. Novak. 1976. The effect of ameliorative measures on the changes of the quality of surface and groundwaters in peat soils. Proc. Fifth Int. Peat Congr. Poznan, Poland, 1976. 1: 118-127.

Gorham, E. 1956a. The ionic composition of some bog and fen waters in the English Lake District. J. Ecol. 44:1: 142-152.

________. 1956b. On the chemical composition of some waters from the Moor House Nature Reserve. J. Ecol. 44:2: 375-382.

Heikurainen, L. 1957. Metsaojien syvyys ja ojituksen tiheys. Eripainos Metsataloudellisesta Aikakauslehdesta. pp. 6-7.

________. 1964. Improvement of forest growth on poorly drained peat soils. Int. Review of Forestry Research. 1: 39-113.

________. 1971. The need for forest drainage and the risks involved. Economic Review. 4:156-170.

________. 1975. Hydrological changes caused by forest drainage. Int. Symp. on the Hydrol. of Marsh-Ridden Areas. UNESCO, Minsk, 1972. pp. 493-499.

________. 1976. Comparison between runoff conditions on a virgin peatland and a forest drainage area. Proc. Fifth Int. Peat Congr., Poznan, Poland, 1976. 1:76-86.

Heinselman, M. 1963. Forest sites, bog processes, and peatland types in the Glacial Lake Agassiz Region, Minnesota. Ecol. Monogr. 33:327-374.

________. 1970. Landscape evolution, peatland types, and the environment in the Lake Agassiz Peatlands Natural Area, Minnesota. Ecol. Monogr. 40: 235-261.

Hommik, K. T. and G. I. Madissoon. 1975. Effects of fen bog draining on the annual runoff under the conditions of the Estonian S.S.R. Int. Symp. on the Hydrol. of Marsh-Ridden Areas. UNESCO, Minsk, 1972. pp. 487-492.

Huikari, O., K. Paarlahti, E. Paavilainen, and H. Ravela. 1966. On the effect of strip-width and ditch-depth on the water economy and runoff on a peat soil. Communicationes Instituti Forestalis Fenniae. 61:8.

Ivitskii, A. I. 1938. Evaporation from peat soil in relation to climatic factors and water table (Russian Transl. IPST 1977). Pochvovedenie 2: 267-281.

Kittredge, J. 1948. Forest Influences. New York. McGraw-Hill Book Co. 394 p.

Klueva, K. A. 1975. The effect of land reclamation by drainage on the regime of rivers in Byelorussia. Int. Symp. on the Hydrol. of Marsh-Ridden Areas. UNESCO, Minsk, 1972. pp. 419-437.

Klyueva, K. A. 1959. On the effect of marsh drainage on river discharge. (Russian Transl. PST 275). Meteorologiya i Gidrologiya. 6: 17-20.

Korchunov, S., Y. Kuskov, I. Krestin, A. Savostyanova, Y. Krasnov, and V. Pokamestov. 1976. Drainage and preparation of peat deposits for peat winning with due regard to utilization of cut-away and lowmoor lands in agriculture and forestry. Proc. Fifth Int. Peat Congr., Poznan, Poland. 1976. 3: 313-326.

Korpijaakko, E. and P. E. Pheeney. 1976. Transport of peat sediment by the drainage system from exploited peatlands. Proc. Fifth Int. Peat Congr., Poznan, Poland, 1976. 1: 135-148.

Kozlovskaya, L. S. 1963. Role of soil organisms in decomposition of organic remains in swamped forest soils. The Increase of Productivity of Swamped Forests. Izdatel'stvo Akademii Nauk S.S.R., Moskva. 49: 27-38.

Kuntze, H. 1976. Soil conservation on cultivated peatlands. Proc. Fifth Int. Peat Congr., Poznan, Poland. 1976. 1: 256-269.

Largin, I. F., I. A. Pal'min, G. V. Nenast'yeva, and O. A. Zelenaya. 1976. Research on chemical composition and properties of water runoff from cutaway raised peat bogs. Torf. Prom. 11:8-10.

Lavrov, A. P., M. V. Fadeyeva, G. I. Sachok, A. P. Vahkovsky, and V. F. Vasilyev. 1975. Problems of groundwater regime and its prediction in drained regions of the Byelorussian Polessie. Int. Symp. on the Hydrol. of Marsh-Ridden Areas. UNESCO, Minsk, 1972. pp. 447-460.

MacDougall, D. and S. H. Richards. 1948. The winning, harvesting, and utilization of peat. Dept. of Scientific and Industrial Research. London: His Majesty's Stationary Office. 24 p.

Malmstrom, C. 1928. Vara torvmarker ur skogsdikningssynpunkt. (Our peat areas from the point of forest-draining.) Centraltryckeriet, Stockholm. 372 p.

Morris, R. E. 1949. Practical aspects of controlled drainage. Agr. Engr. 30:280-283.

MRI (Midwest Research Institute), 1976. A report on European peat technology. Minneapolis, Minnesota. 48 p.

Mustonen, S. 1964. Ojituksen Vaikutuksesta Suon Hydrologiaan. (On the effect of drainage on hydrology of peat land.) Rakennusteknikka. 3: 204-209.

Mustonen, S. E. and P. Seuna. 1975. Influence of forest draining on the hydrology of an open bog in Finland. Int. Symp. on the Hydrol. of Marsh-Ridden Areas, UNESCO, Minsk, 1972. pp. 519-530.

Nesterenko, I. M. 1976. Subsidence and wearing out of peat soils as a result of reclamation and agricultural utilization of marshlands. Proc. Fifth Int. Peat Congr., Poznan, Poland. 1976. 1:218-232.

Olkowski, M. and L. Olesinski. 1976. Changes of peat bogs environment of northeastern Poland as a result of human intervention. Proc. Fifth Int. Peat Congr., Poznan, Poland. 1976. 1:183-190.

Paivanen, J. 1974. Hydrologic effects of clear-cutting in peatland forests. Proc. Int. Symp. on Forest Drainage, Jyvaskyla-Oulu, Finland. Helsinki. pp. 219-228.

Plummer, C. E. 1949. Report of progress in peat development. Office of the Commissioner of the Iron Range Resource and Rehabilitation. 142 p.

Post, F. A. and F. R. Dreibelis. 1942. Some influences of frost penetration and microclimate on the water relationships of woodland pasture, and cultivated soils. Soil Sci. Soc. Amer. Proc. 7:95-104.

Prus-Chacinski, T. M. and W. B. Harris. 1963. Standards for lowland drainage and flood alleviation and drainage of peat lands, with special reference to the Crossens Scheme. Proc. Inst. Civil Engr. 24:177-206.

Robertson, I. M. 1933. Peat mosses - II. The draining of peat land. Scottish J. Agr. 16:2:160-172.

Romanov, V. V. 1962. Isparenie s bolot Evropeiskoi territorii SSSR. (Evaporation from bogs in the European territory USSR.) Gimiz, Gidrometeorologicheskoe Izdatel'stvo, Leningrad. (Russian Transl. IPST 1968) 183 p.

Schothorst, C. J. 1976. Subsidence of low moor peat soils in the western Netherlands. Proc. Fifth Int. Peat Congr., Poznan, Poland. 1976. 1:206-217.

Sparling, J. H. 1966. Studies on the relationship between water movement and water chemistry in mires. Can. J. Botany. 44:747-758.

Steelink, C. 1977. Humates and other natural organic substances in the aquatic environment. J. Chemical Education 54:599-603.

Storey, H. C. 1955. Frozen soil and spring and winter floods. U.S. Dept. Agr. Yearbook, 1955. pp. 179-185.

Tallis, J. H. 1973. Studies on southern pennine peats. V. Direct observations on peat erosion and peat hydrology at Featherbed Moss, Derbyshire. J. Ecol. 61:1:1-22.

van der Molen, W. H. 1975. Subsidence of peat soils after drainage. Int. Symp. on the Hydrol. of Marsh-Ridden Areas, UNESCO, Minsk, 1972. pp. 183-186.

Verry, E. S. 1975. Streamflow chemistry and nutrient yields from upland-peatland watersheds in Minnesota. Ecol. 56:1149-1157.

Verry, E. S. and D. H. Boelter. 1975. The influence of bogs on the distribution of streamflow from small bog-upland catchments. Int. Symp. on the Hydrol. of Marsh-Ridden Areas, UNESCO, Minsk, 1972. pp. 469-478.

Vidal, H. 1960. Vergleichende Wasserhaushalts und Klimabeobachtungen auf unkultivierten und Kultivierten Hochmooren in Sudbayern. (Comparative hydrologic balances and meteorologic observations on uncultivated and cultivated highmoors in southern Bavaria.) Herausgegeben von der bayerischen Landesanstalt für Landkultur und Moorwirtschaft. Munchen 23, 8:2/3:50-108.

Walmsley, M. E. and L. M. Lavkulich. 1975. Chemical, physical and land use investigations of organic terrain. Can. J. Soil Sci. 55:331-342.

Weitzman, S. and R. R. Bay. 1963. Forest soil freezing and the influence of management practices, northern Minnesota. USDA For. Serv., Res. Paper LS-2, Lake States For. Exp. Stn., St. Paul, Minnesota 8 p.

Wisler, C. O. and E. F. Brater. 1959. Hydrology. John Wiley and Sons, Inc., New York, 408 p.

APPENDIX

CONCEPTUAL HYDROLOGIC MODEL

OF PEATLANDS

STEVEN R. PREDMORE

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The final recommendation of the preceding report suggested the development of models capable of estimating the hydrologic response of peatlands. While the prediction of both water yield and water quality characteristics of natural and harvested peatlands are the ultimate goals, the important hydrologic processes which affect the yield and timing response from watersheds need to be quantified. The specific objectives of this model are to estimate maximum discharge, minimum discharge, and total water yield of peatlands before and after extraction. The hydrologic processes modeled, and suggestions about how such processes are linked together are discussed herein. Also, mathematical equations used to describe hydrologic processes will be reported along with the methods of estimating equation variables. Although the projected model has not been tested, it represents a first step in the development of a peatland hydrology model.

MODELING PEATLAND HYDROLOGIC PROCESSES

Hydrologic modeling of peatlands requires that the processes of water storage and flow through the plant-soil system be qualified. The conceptual components are illustrated in Figure A-1. Precipitation, a major input to the model, enters the hydrologic system as rain or snow. An initial assumption of the model is that rainfall is subject to interception loss by vegetation while snowfall, although intercepted, is not lost from the system. A percentage of snowmelt and net rainfall may contribute to impervious area runoff as discussed later. The remaining portion enters surface storage which represents depression storage plus any addition to overload flow.

The infiltration process determines how much of the surface storage enters the peat profile. The peat profile is partitioned into three zones (Figure A-2). Zone 1 is the upper most layer and is subject to the processes of infiltration, evapotranspiration, vertical percolation, and subsurface lateral flow or interflow. The occurrence of interflow is the most important characteristic of this zone. The depth of Zone 1 is the average depth to the water table within the peatland when peatland outflow ceases. This depth varies from peatland to peatland. Heinselman (1963) reported that outflow ceased when the water table reached a depth of 6 to 15 inches (15 to 38 cm) at various points in an extensive peatland in the Lake Agassiz Region. An average depth for Zone 1 of this peatland would be about 11 inches (28 cm).

Zone 2, underlying Zone 1, exhibits the same hydrologic processes with the exception of interflow. The lower limit of Zone 2 represents the boundary of evapotranspiration loss. It is determined by the depth of active plant roots. Black spruce is likely the deepest rooted vegetation with a root system which may extend to 20 inches (51 cm) in organic soils (U.S. Forest Service, 1965). The average depth of active roots for a particular watershed should be determined by field inspection but for the purpose of illustration Zone 2 could be considered to extend from 11 to 20 inches (28 to 51 cm). This zone can be eliminated if the active rooting depth is less than the depth of Zone 1.

Downward percolation of water out of Zone 2 will not occur if the substratum is impermeable. Overwinter recession of the actual peatland water table below Zone 2 indicates permeable mineral substratum and the need for a third zone. At various locations within the Lake Agassiz peatland mentioned

...ously, the water table dropped from 17 to 38 inches (43 to 97 cm) ...ri... the period December 1 to early March (Heinselman, 1963). In this ...ce Zone 3 is required to model the loss of water from the peatland. ...ld extend from 20 inches (51 cm) to the average depth of peat.

...vapotranspiration (ET) losses are represented by interception and ...e evaporation and Zone 1 and Zone 2 transpiration. Interception and ...e are assumed to evaporate at the potential rate. The rate of ET ...one 1 and Zone 2 is a function of their moisture content. Vapor ... from snowpack and deep groundwater storage are neglected.

...verland flow and interflow are the components of the model which ...oute to the outflow hydrograph. A single flow plane of depth equal ... 1, width equal to the average flow length, and length equal to the ...of the outflow channel is used to represent the peatland. Inflow to ...nnel from overland flow and interflow is routed to the peatland outlet ...ischarge and water yield values are determined.

Hydrologic Processes

...e specific equations and parameters used by component models to pre... ...tflow from peatlands will now be presented. Their linkages within ...land model and the specific operation of the model is discussed and ...ted in the following sections. Input data required by the model ...n in Table A-1.

...tion

... interception subroutine (Figure A-3) treats interception storage ...ket, which has a maximum capacity when empty and must be filled be... ...cipitation reaches the peatland surface. Gross rainfall is the input to the interception "bucket" and net rainfall is equal to gross precipitation minus the interception storage. Interception storage is reduced at the potential ET rate until interception storage is zero.

Values of interception capacity can be obtained from the literature for many species at various densities. Sources of interception values are Zinke (1967) and Gray (1970). To determine the interception capacity of the watershed, the percentage of the watershed consisting of forest, brush, herbaceous, and open cover types must be known. Then sum the product of cover type area as a precentage of the watershed and the interception capacity of the cover type. This procedure is represented by the following:

$$I_f = C_f \, A_f \qquad (1.1)$$

$$I_b = C_b \, A_b \qquad (1.2)$$

$$I_h = C_h \, A_h \qquad (1.3)$$

$$I_w = I_f + I_b + I_h \qquad (1.4)$$

where

I_w = interception capacity of the watershed

I_f, I_b, I_h = interception capacity of forest, brush, and herbaceous areas of the watershed respectively.

C_f, C_b, C_h = Interception capacity of forest, brush, and herbaceous cover types respectively.

A_f, A_b, A_h = Percentage of the watershed in forest, brush, and herbaceous cover types respectively.

The percentage of the watershed consisting of a particular cover type and the average density of vegetation may be estimated from aerial photographs and ground checking.

The maximum interception storage capacity of a watershed will change as drained or undrained peat harvesting occurs. Knowing the size and location of the harvesting operation within the watershed allows revision of the cover type acreages and average cover type densities. A new value of interception capacity may then be computed.

Snowmelt

Snowmelt occurs as a result of absorbed shortwave and net longwave radiation (U.S. Army Corps of Engineers, 1956). Radiation inputs to the snowmelt process may vary with the amount of forest cover, therefore, the method of computing snowmelt must take this into account. Both the General Snowmelt equations by the Corps of Engineers (1956) and the Leaf-Brink model as modified by Solomon, et al. (1976) fulfill this requirement. Either of the above models would be used in conjunction with the peatland conceptual model.

Peat harvesting by both drained and undrained methods may increase the melt rate by decreasing the percentage of the watershed in forest cover and thereby increasing the amount of shortwave radiation and net rainfall reaching the snow surface.

Impervious Area

Impervious area represents that percentage of the watershed which is covered by channel surfaces, open ponds or lakes (those which have an outlet), and vehicle roadways. This percentage is multiplied by the net rainfall or snowmelt to compute the impervious area input rate to channel flow. The equations used in Figures A-3 and A-5 are:

$$Q_i = A_j P \qquad (1.6)$$

$$Q_i = A_j S \qquad (1.7)$$

where

Q_i = impervious area contribution to channel (in/hr)

A_j = percentage of the watershed impervious as a fraction

P = net rainfall (in or cm/hr)

S = snowmelt (in or cm/hr)

The impervious area of a watershed may be estimated by aerial photographs or field inspection. The effect of harvesting, either drained or undrained, on the value of impervious area can be computed if the area dimensions of open water, drainage ditches, roads, and natural channels are known.

Infiltration

The rate at which snowmelt and net rainfall infiltrate the soil surface influences both surface and subsurface water movement. Likewise, surface and subsurface hydrologic processes influence the rate of infiltration. Therefore, the modeling of infiltration must interact with other hydrologic processes within the land-phase subroutine (Figure A-5).

Several infiltration equations are available to estimate infiltration rates. Unfortunately, many of these, including the well known Horton (1933) and Philip (1954) equations, compute infiltration as a function of time and may not accurately predict infiltration rates for two-stage infiltration events and intermittant storms. Holtan's (1961) equation is used in this model because it computes infiltration as a function of soil moisture. In this manner Holtan's (1961) equation indirectly represents the matric forces which play a major role in the infiltration process:

$$F = F_c + A\ (SM - S)^n \qquad (5.1)$$

where

F = infiltration rate at time x (in or cm/hr)

F_c = final infiltration rate (in or cm/hr)

SM = total saturated moisture content of zones 1, 2, and 3 (in or cm)

S = soil moisture content at the time of estimate (in or cm)

A,n = constants

The final infiltration rate occurs when the entire peat profile becomes saturated. At this time the inflow of water to the soil can occur only as fast as the outflow from the soil system. Theoretically speaking, the final infiltration rate equals the rate of loss from Zone 3 plus the rate of interflow. With this in mind, several methods may be used to estimate the final infiltration rate of the peatland. Field apparatus such as a double-ring infiltrometer may be utilized to determine the final infiltration rate. To get the best estimate the apparatus should be used when all zones are saturated and soil frost is gone. These conditions may be difficult to find. Another alternative is to compute the rate of interflow from the average Zone 1 saturated hydraulic conductivity and Darcy's Law. Interflow computed in this manner could be added to the Zone 3 loss rate to estimate the final infiltration rate. Finally, when the Zone 3 loss rate is unknown, estimate the loss rate using Darcy's Law and the saturated hydraulic conductivity of the most decomposed peat within Zone 3 or the saturated hydraulic conductivity of the mineral substratum whichever is lowest. Add this to the rate of interflow as computed above to estimate the final infiltration rate. Values of saturated hydraulic conductivity for fibric, hemic, and sapric peats are shown in Figure 1 of the preceding report. The saturated soil moisture content used in Holtan's (1961) equation should be the sum of the saturated moisture contents of all 3 zones. The saturated soil moisture content of each zone may be estimated by multiplying the saturated volumetric moisture content for the average peat type of the zone (Figure 2 in preceding text) times the depth of the zone.

The soil moisture content at the time of estimate should be the total moisture content within all three zones since all are saturated when the final infiltration rate occurs. The initial moisture content of each zone must be specified as input to the model. It is easiest to apply the model for spring conditions when all zones are saturated. Thereafter, the soil moisture content at the midpoint and endpoint of the computing time interval is determined for each zone by continuity equations which estimate changes in storage as inflow to a zone minus outflow from the zone. Initial midpoint and endpoint infiltration rates are computed using the appropriate total moisture content. Endpoint values of soil moisture content and infiltration rate become initial values for the next time increment. Zone 1 midpoint and endpoint moisture contents are determined as follows:

$$S_{1m} = S_{1i} \; \Delta t/2 \; (F_{1i} - QI_{1i} - P_{1i} - ET_{1i}) \tag{5.2}$$

$$S_{1n} = S_{1i} + \Delta t \; (F_{1m} - QI_{1m} - F_{1m} - ET_{1m}) \tag{5.3}$$

where

S_{1m}, S_{1n} = moisture content of zone 1 at the midpoint and endpoint of the time interval respectively (in or cm/hr)

S_{1i} = moisture content of Zone 1 at the beginning of the time interval (in or cm)

Δt = Time interval between estimates (hr)

F_{1i}, F_{1m} = infiltration rate of zone 1 at the beginning and midpoint of the time interval respectively (in or cm/hr)

QI_{1i}, QI_{1m} = interflow rates of zone 1 at the beginning and midpoint of the time interval respectively (in or cm/hr)

P_{1i}, P_{1m} = percolation rates out of zone 1 at the beginning and mid-point of the time interval respectively (in or cm/hr)

ET_{1i}, ET_{1m} = evapotranspiration rate of zone 1 at the beginning and midpoint of the time interval respectively (in or cm/hr)

For Zone 2:

$$S_{2m} = S_{zi} + \Delta t/2\ (P_{1i} - P_{2i} - ET_{2i}) \tag{5.4}$$

$$S_{2n} = S_{2i} + \Delta t\ (P_{1m} - P_{2m} - ET_{2m}) \tag{5.5}$$

where

S_{2m}, S_{2n} = moisture content of zone 2 at the midpoint and endpoint of the time interval respectively (in or cm)

S_{zi} = moisture content of Zone 2 at the beginning of the time interval (in or cm)

P_{2i}, P_{2m} = percolation rates out of Zone 2 at the beginning and midpoint of the time interval respectively (in or cm/hr)

ET_{2i}, ET_{2m} = evapotranspiration of zone 2 at the beginning and midpoint of the time interval respectively (in or cm/hr)

For Zone 3:

$$S_{3m} = S_{3i} + \Delta t/2\ (P_{2i} - P_{3i}) \tag{5.6}$$

$$S_{3n} = S_{3i} + \Delta t\ (P_{2m} - P_{3m}) \tag{5.7}$$

where

S_{3m}, S_{3n} = moisture content of zone 3 at the midpoint and endpoint of the time interval respectively (in or cm)

S_{3i} = moisture content of zone 3 at the beginning of the time interval (in or cm)

P_{3i}, P_{3m} = percolation or loss rate from zone 3 at the midpoint and endpoint of the time interval respectively (in or cm/hr)

The constants A and n in Holtan's (1961) equation must be evaluated by fitting. This requires that actual infiltration rates be determined perhaps using a double-ring infiltrometer. Plot the observed infiltration rate vs time and choose two points near the beginning of the curve. Knowing the initial total moisture content, the total moisture content at each of the two points can be determined by computing the amount of water which infiltrated up to that point. Add the value of infiltrated water to the initial total moisture content and the total moisture content at each point is known. Plug in the observed infiltration rate, final infiltration rate, saturated total moisture content, and total moisture at the time of measurement into the Holtan (1961) equation for each of the two points. Only A and n are unknown. With two equations and two unknowns, solve the equations simultaneously for values of A and n. After values of A and n are computed for fibric, hemic, and sapric peats field trials may not be necessary for each peatland watershed if the type of surface peat is known.

Modeling the effects of soil frost on infiltration will be complicated and will require some field experimentation to identify basic relationships between infiltration rates and soil frost for natural and harvested areas. If concrete frost forms in zone 1, a new zone 1 depth must be adjusted to equal the upper elevation of concrete frost. For instance, during late winter, concrete frost may be present at the peatland surface. The depth of zone 1 and the infiltration rate would be zero. However, the upper limit of concrete frost may be an inch below the peatland surface in spring. The depth of zone 1 is now an inch and new values of saturated moisture content, saturated hydraulic conductivity, zone 1 moisture content, and final infiltration rate must be established before the model can be applied. Although empirical, perhaps a multiple regression of climatological and physical peatland characteristics could be used to predict frost depth. Another possibility is to estimate the depth of soil frost by a degree-day relationship.

Infiltration rates will change following drained peat harvesting as different peats occupy zones 1, 2, and 3. The values of saturated total moisture, final infiltration rate, and constants A and n of Holtan's (1961) equation may require adjustment. An estimate of the type of peat in these zones will allow the variables in Holtan's (1961) equation to be evaluated if infiltration vs time data is available for fibric, hemic, and sapric peats. New values for the entire watershed may then be determined by computing a weighted average based on the percentage of the watershed in a harvested and unharvested condition.

Overland Flow

Overland flow is modeled as a function of both surface and depression storage (Figure A-5). When surface storage exceeds depression storage overland flow begins. The initial value for surface storage is input to the model. Thereafter, the midpoint and endpoint values of surface storage are computed by:

$$S_{sm} = S_{si} + \Delta t/2\ (P + S - F_{li} - QO_i - PET) \tag{5.8}$$

$$S_{sn} = S_{si} + \Delta t\ (P + S - F_{lm} - QO_m - PET) \tag{5.9}$$

where

S_{sm}, S_{sn} = Midpoint and endpoint surface storage (in or cm)

S_{si} = surface storage at the beginning of the time interval (in or cm)

QO_i, QO_m = initial and midpoint overland flow rate (in or cm/hr)

PET = potential rate of evapotranspiration (in or cm/hr)

The difference between initial, midpoint, and endpoint surface storage and a constant value of depression storage determines the initial, midpoint, and endpoint values of overland flow storage, respectively.

In equation form:

$$S_{oi} = S_{si} - S_d \qquad (5.10)$$

$$S_{om} = S_{sm} - S_d \qquad (5.11)$$

$$S_{on} = S_{sn} - S_d \qquad (5.12)$$

where

S_{oi}, S_{om}, S_{on} = initial, midpoint, and endpoint overland flow storage (in or cm)

S_{si}, S_{sm}, S_{sn} = initial, midpoint, and endpoint surface storage (in or cm)

S_d = Depression storage (in or cm)

Finally, overland flow is computed at the beginning, midpoint, and endpoint of the time interval by the following storage-outflow equation in the land phase subroutine.

$$QO_i = cS_{oi}^{\ x} \qquad (5.13)$$

$$QO_m = cS_{om}^{\ x} \qquad (5.14)$$

$$QO_n = cS_{om}^{\ x} \qquad (5.15)$$

where

QO_n = Endpoint overland flow rate (in or cm/hr)

c, x = constants

Values of depression storage may be considerable for natural peatlands. Heinselman (1963) reported areas of bog ridges situated normal to the direction of flow near Red Lake as having dimensions approximately one foot in height, and spaced 10 to 50 feet apart. Some water flowed in pathways around these ridges so that depression storage was not one foot in depth. However, depression storage in undisturbed peatlands could amount to several centimeters. Milled or block harvesting methods will tend to eliminate depression storage and create a smooth flow plane which would likely speed up overland flow during a rainfall or snowmelt event.

Interflow

Subsurface lateral flow or interflow will be computed only in zone 1 when the zone 1 moisture content exceeds field capacity. The difference between zone 1 moisture content and zone 1 field capacity is the input to the interflow process. The depth of interflow is computed for the initial, midpoint, and endpoint of the time increment as follows:

$$QID_i = CD\ (S_{1i} - S_{1fc}) \tag{5.16}$$

$$QID_m = CD\ (S_{1m} - S_{1fc}) \tag{5.17}$$

$$QID_n = CD\ (S_{1n} - S_{1fc}) \tag{5.18}$$

where

QID_i, QID_m, QID_n = depth of interflow at the initial, midpoint, and endpoint of the time interval (in or cm/hr)

CD = depth coefficient

S_{1fc} = Zone 1 moisture content at field capacity (in or cm)

The depth coefficient is equal to the depth of zone 1 (in or cm) divided by the saturated moisture content of zone 1 (cm). The field capacity of zone 1 may be determined by multiplying the 0.1 bar volumetric moisture content shown in Figure 2 (previous text) by the depth of zone 1. Darcy's Law is used to compute the initial, midpoint, and endpoint interflow rates based on the depth of interflow as follows:

$$QI_i = (QID_i\ \ S_{1k}\ \ S_e)/L_f \tag{5.19}$$

$$QI_m = (QID_m\ \ S_{ik}\ \ S_e)/L_f \tag{5.20}$$

$$QI_n = (QID_n\ \ S_{ik}\ \ S_e)/L_f \tag{5.21}$$

where

S_{1k} = Zone 1 saturated hydraulic conductivity (in or cm/hr)

S_e = average land slope

L_f = length of flow (in or cm)

Saturated hydraulic conductivity values are reported for different peats in Figure 1 of the previous text and may be used if the average peat type of zone 1 is known. Figure 1 values require unit conversion. The average land slope represents the slope of the flow plane and the hydraulic gradient in Darcy's Law. Its value can be determined from topographic maps if available or from on-site inspection. The length of flow is time average distance from the watershed boundary to the channel and represents the length of the flow plane normal to the watershed channel.

The impacts of drained harvesting methods on interflow can be estimated by the model if the type of peat located in zone 1 after harvesting is known along with the length of flow between ditches and the hydraulic gradient or land slope determined by ditch depth over length of flow between ditches.

Percolation

Percolation is the downward movement of water through the peat profile. Like interflow, percolation occurs only when the moisture content exceeds field capacity. The Huggins and Monke (1968) equation is used to estimate percolation because of its similarity to the Holtan (1961) infiltration equation. Like the Holtan (1961) equation, the Huggins and Monke (1968) equation computes downward water movement as a function of moisture content rather than time. Since deep seepage loss is assumed to occur from zone 3, this equation is applied to all three zones at the initial, midpoint, and endpoint of the time interval as fol'ows:

$$P_{1i} = \left(\frac{S_{1i} - S_{1fc}}{SM_1 - S_{1fc}}\right)^3 (P_c) \qquad (5.22)$$

$$P_{1m} = \left(\frac{S_{1m} - S_{1fc}}{SM_2 - S_{1fc}}\right)^3 (P_c) \qquad (5.23)$$

$$P_{1n} = \left(\frac{S_{1n} - S_{1fc}}{SM_1 - S_{1fc}}\right)^3 (P_c) \qquad (5.24)$$

$$P_{2i} = \left(\frac{S_{2i} - S_{2fc}}{SM_2 - S_{2fc}}\right)^3 (P_c) \qquad (5.25)$$

$$P_{2m} = \left(\frac{S_{2m} - S_{2fc}}{SM_2 - S_{2fc}}\right)^3 (P_c) \qquad (5.26)$$

$$P_{2n} = \left(\frac{S_{2n} - S_{2fc}}{SM_2 - S_{2fc}}\right)^3 (P_c) \qquad (5.27)$$

$$P_{3i} = \left(\frac{S_{3i} - S_{3fc}}{SM_3 - S_{3fc}}\right)^3 (P_c) \qquad (5.28)$$

$$P_{3m} = \left(\frac{S_{3m} - S_{3fc}}{SM_3 - S_{3fc}}\right)^3 (P_c) \qquad (5.29)$$

$$P_{3n} = \left(\frac{S_{3n} - S_{3fc}}{SM_3 - S_{3fc}}\right)^3 (P_c) \qquad (5.30)$$

where

P_{1i}, P_{1m}, P_{1n} = percolation rate of zone 1 at beginning, midpoint, and endpoint of time interval (in or cm/hr)

P_{2i}, P_{2m}, P_{2n} = percolation rate of zone 2 at beginning, midpoint, and endpoint of time interval (in or cm/hr)

P_{3i}, P_{3m}, P_{3n} = percolation rate of zone 3 at beginning, midpoint, and endpoint of time interval (in or cm/hr)

S_{1fc} = zone 1 field capacity moisture content (in or cm)

S_{2fc} = zone 2 field capacity moisture content (in or cm)

S_{3fc} = zone 3 field capacity moisture content (in or cm)

SM_1 = saturated moisture content of zone 1 (in or cm)

SM_2 = saturated moisture content of zone 2 (in or cm)

SM_3 = saturated moisture content of zone 3 (in or cm)

P_c = saturated percolation rate -- zone 3 loss rate (in or cm/hr)

Values of saturated moisture content for the average peat type within each zone can be obtained from Figure 2 of the preceding text. When all zones are saturated, the rate of downward movement through the profile will equal the zone 3 loss rate. Therefore, this value is used in the Huggins and Monke (1968) equation as the saturated percolation rate.

Drained harvesting will create an upper zone of greater decomposition. These peats will exhibit greater field capacities and lower final infiltration rates which will reduce percolation. The estimation of soil moisture characteristics of the peat zones can be determined from Figure 2 of the preceding text.

Evapotranspiration

Evaporation from undisturbed peatlands is assumed to occur at the potential rate from interception and surface storage. The ET rate of zones 1 and 2, on the other hand, depends upon the moisture content of those zones. This model assumes that ET from a particular storage cannot occur until the overlying storage component is depleted. For example, no evaporation occurs from surface storage until interception storage is zero. Likewise, for zone 1 storage, no ET is deducted until the surface storage is zero. For zone 2 ET to occur, zone 1 storage must be depleted to the wilting point moisture content.

Evaportranspiration from zones 1 and 2 is modeled after research by Holmes (1961) who concluded that the ratio of actual evapotranspiration to potential evapotranspiration decreases as the soil dries out (Gray, 1970). The ET subroutine (Figure A-6) for zone 1 and zone 2 initial and midpoint evapotranspiration are based on the diagram in Figure A-8.[1]

For zone 1 and zone 2 moisture contents greater than one-half the distance between wilting point moisture content and field capacity, evapotranspiration occurs at the potential rate. For moisture contents less than the point indicated by the intersection of the ET curve and the X-axis, evapotranspiration equals zero. At moisture contents between the two values above, evapotranspiration will vary as shown by the sloped line. The mathematical equation used by the model to predict evapotranspiration along the sloped line is:

$$ET_{12i} = (PET)\ C_{et}(S_{1i} + S_{2i}) + B_{et} \qquad (6.1)$$

$$ET_{12m} = (PET)\ C_{et}(S_{1m} + S_{2m}) + B_{et} \qquad (6.2)$$

where

ET_{12i}, ET_{12m} = initial and midpoint evapotranspiration rate from zone 1 and zone 2 (in or cm/hr)

PET = potential evapotranspiration remaining after surface storage is depleted (in or cm/hr)

C_{et} = (0.7) (zone 1 + zone 2 moisture content half way between wilting point and field capacity) (6.3)

B_{et} = (0.3) (A) (Zone 1 + zone 2 wilting point moisture contents) (6.4)

The ratio $\frac{B_{et}}{C_{et}}$ represents the point on the soil moisture axis below which

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[1] Based on course AgEn 8500, the University of Minnesota, Professor Curtis L. Larson, instructor.

zone 1 and zone 2 evapotranspiration equals zero. Like field capacity, figure 2 may be used to estimate the wilting point moisture content of the lower zone. The suction line of 15 bars should be used to represent wilting point suction.

This model may require some modification to estimate ET losses. Drained harvesting methods reduce the forest cover and thereby reduce the depth of soil subject to ET loss. In other words the depth of zone 2 should be reduced. The model may also require slight modification to compute evaporation from closed harvest basins.

Channel Routine

Kinematic routing is the method used to calculate the outflow hydrograph and water yield. The input to a rectangular channel from impervious area, interflow, and overland flow is routed a distance downstream corresponding to the velocity of flow and the time interval. The inflow equation is as follows:

$$Q_c = \frac{A_w\ (Q_i + QO_n + QI_{1n})}{(12)\ (60)\ (60)} * \left(\frac{1}{B_c L_c}\right) \tag{7.1}$$

or

$$Q_c = \frac{A_w\ (Q_i + QO_n + QI_{1n}}{(100)\ (60)\ (60)} * \left(\frac{1}{B_c L_c}\right) \tag{7.2}$$

where

Q_c = inflow to watershed channel (ft/sec or m/sec)

Q_i = impervious area input (in or cm/hr)

QO_n = endpoint overland flow (in or cm/hr)

QI_{1n} = endpoint interflow input (in or cm/hr)

A_w = watershed area (ft^2 or m^2)

B_c = Channel width (ft or m)

L_c = channel length (ft or m)

The depth function specified by the kinematic model is:

$$YP_x = YM_x - (\Delta t/\Delta x)\ (QM_x - QL_x) + (Q_c)(\Delta t) \qquad (7.3)$$

where

YP_x = depth of flow at point x (ft. or m)

YM_x = previous depth of flow at point x (ft. or m)

Δt = time interval (sec)

Δx = distance interval (ft. or m)

QM_x = previous discharge at point x (ft^2/sec)

QL_x = previous discharge one x increment upstream

The flow function is Mannings equation as follows:

$$QP_x = \frac{1.49\ YP_x\ R^{2/3}\ S_c^{\ 1/2}}{n} \quad \text{or} \quad QP_x = \frac{YP\ R^{2/3}\ S_c^{\ 1/2}}{n}$$

where

QP_x = discharge per unit width of channel (ft^2/sec or m^2/sec)

R = hydraulic radius

S_c = channel slope

n = Mannings n

When the watershed outlet is reached:

$$Q_d = QP_x B$$

and

$$Qt = Qt_{-1} + (Q_c)\ (\Delta t)$$

where

Q_d = discharge (ft^3/sec or m^3/sec)

B = channel width (ft or m)

Qt = total water yield at time (ft^3 or m^3)

Qt_{-1} = total water yield at previous time interval (ft^3 or m^3)

Δt = time increment (sec)

Peat harvesting may affect the channel characteristics of the watershed. The impact of drained peat harvesting may be to decrease Mannings n. The impacts of drained peat harvesting on channel flow may then be estimated by reducing Mannings n.

Table A-1. Input Data

Hourly potential evapotranspiration

Gross precipitation

Daily mean temperature.

Percent impervious area

Forest interception capacity

Brush interception capacity

Herbaceous interception capacity

Percent forested area

Percent brush area

Percent herbaceous area

Percent of watershed in harvest basins

Zone 1 saturated moisture content

Zone 1 field capacity

Zone 2 staturated moisture content

Zone 2 field capacity

Zone 1 saturated hydraulic conductivity

Zone 2 saturated hydraulic conductivity

Depression storage

Snow storage

Initial water content in interception, surface, Zone 1 and Zone 2 storages, Zone 3, total soil storage (Zone 1 + Zone 2 + Zone 3), depression storage

Total saturated moisture content

Zone 3 saturated moisture content

Zone 3 field capacity

Zone 3 saturated hydraulic conductivity or substratum saturated hydraulic conductivity

Depression storage capacity

Depth to water table

Figure A-1

Peatland Conceptual Hydrologic Model

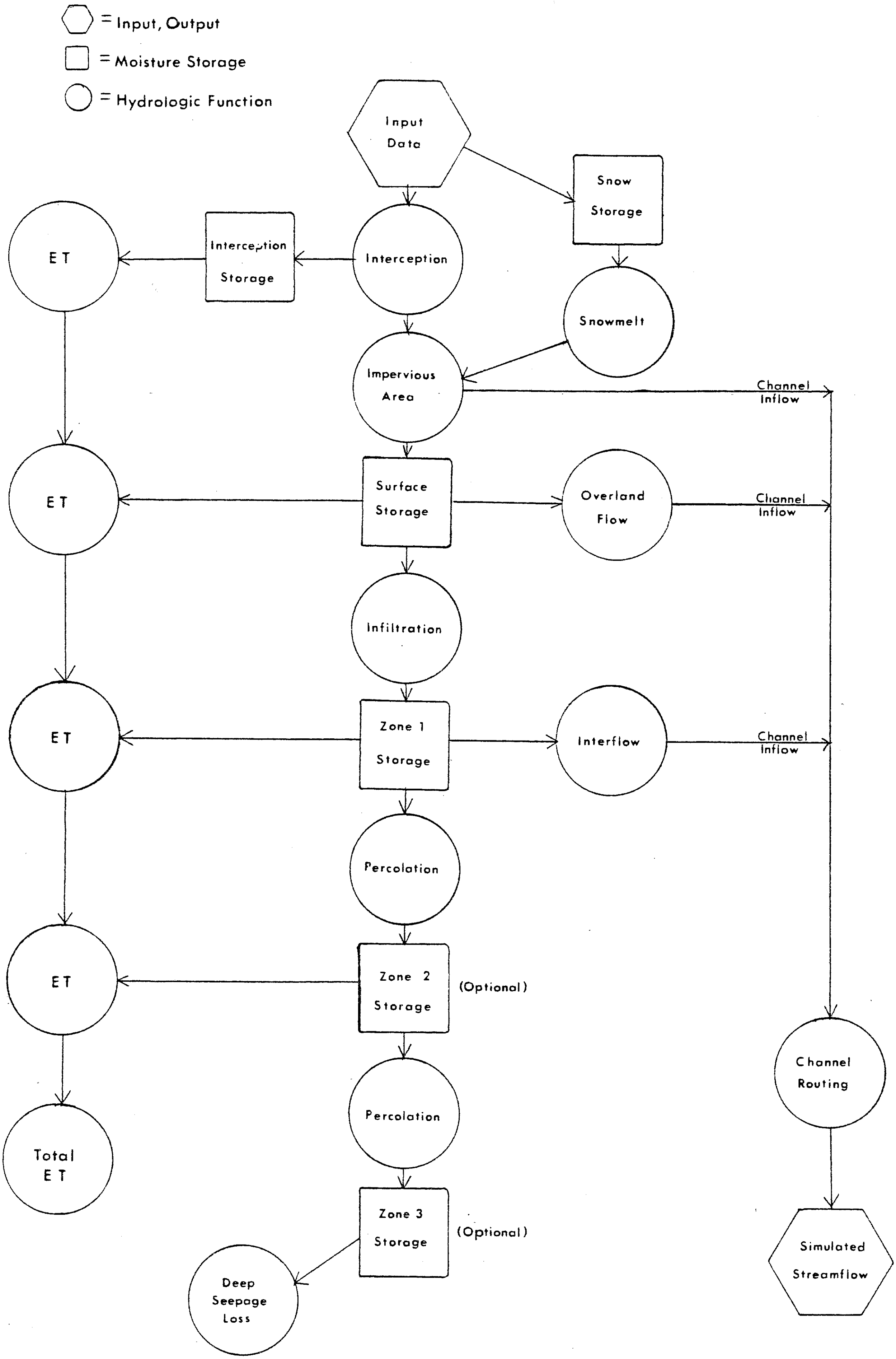


Figure A-2

Hydrologic Processes of Peatland

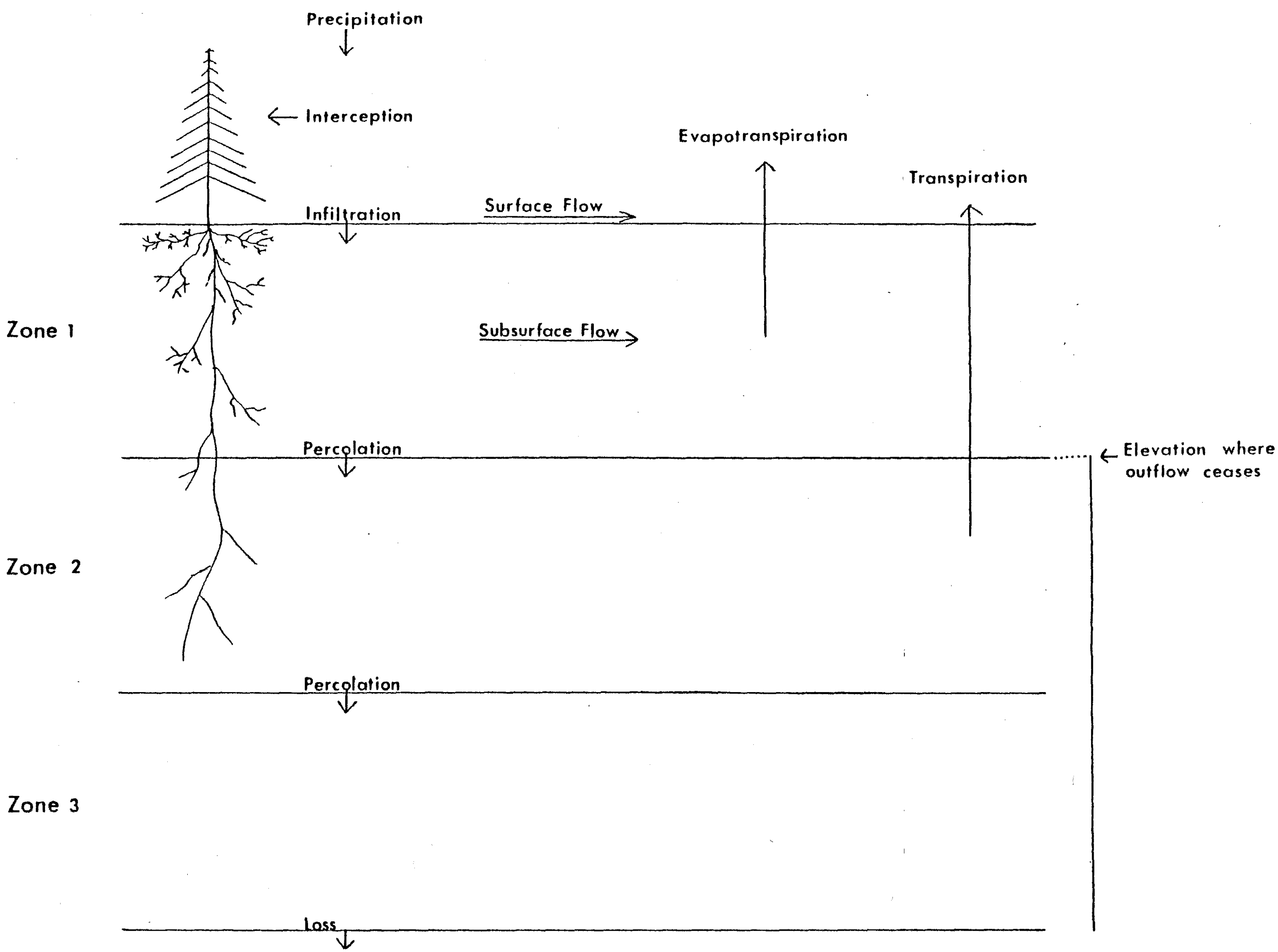


Figure A-3

OVERVIEW OF MODEL STRUCTURE

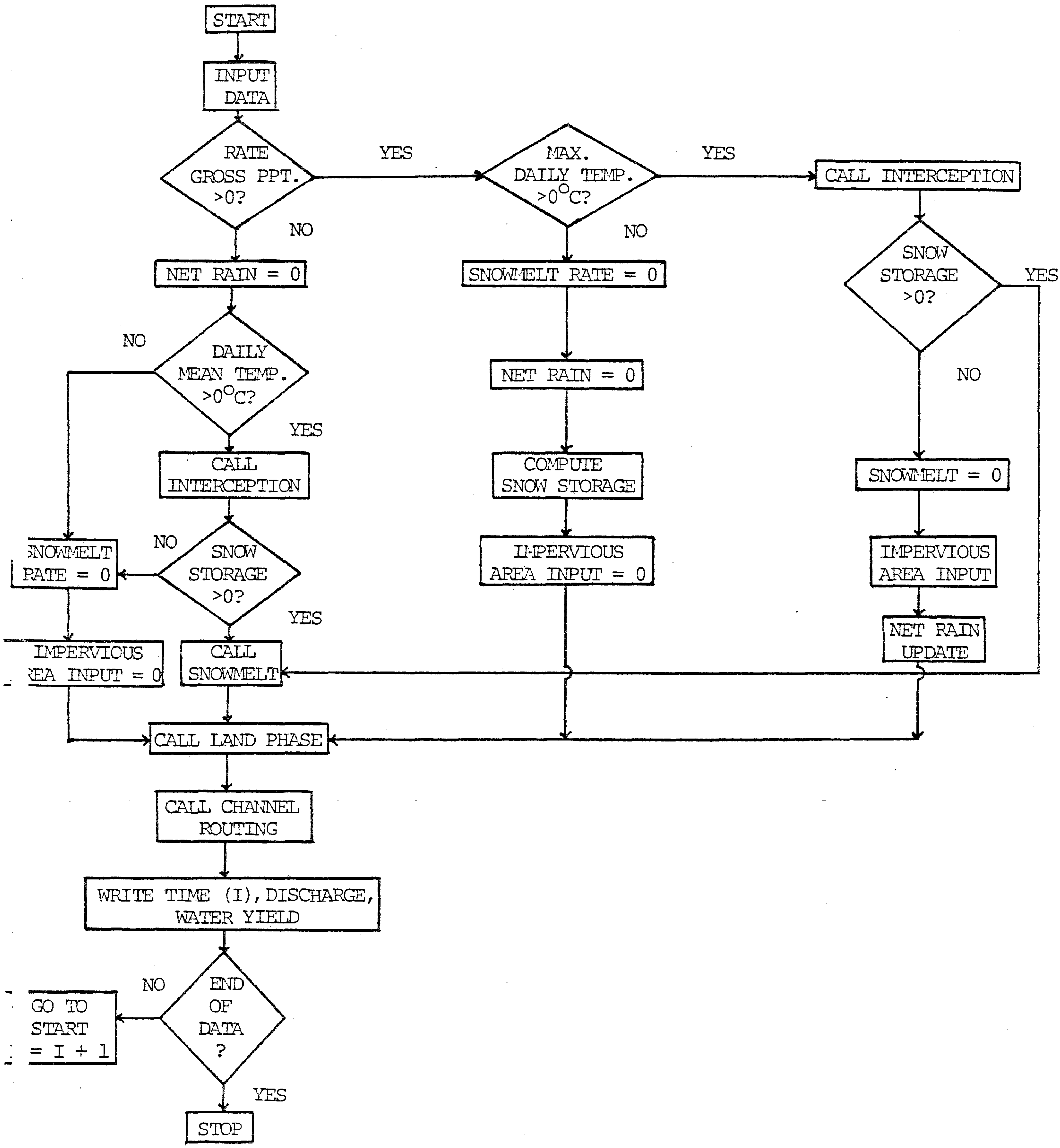


Figure A-4

INTERCEPTION SUBROUTINE

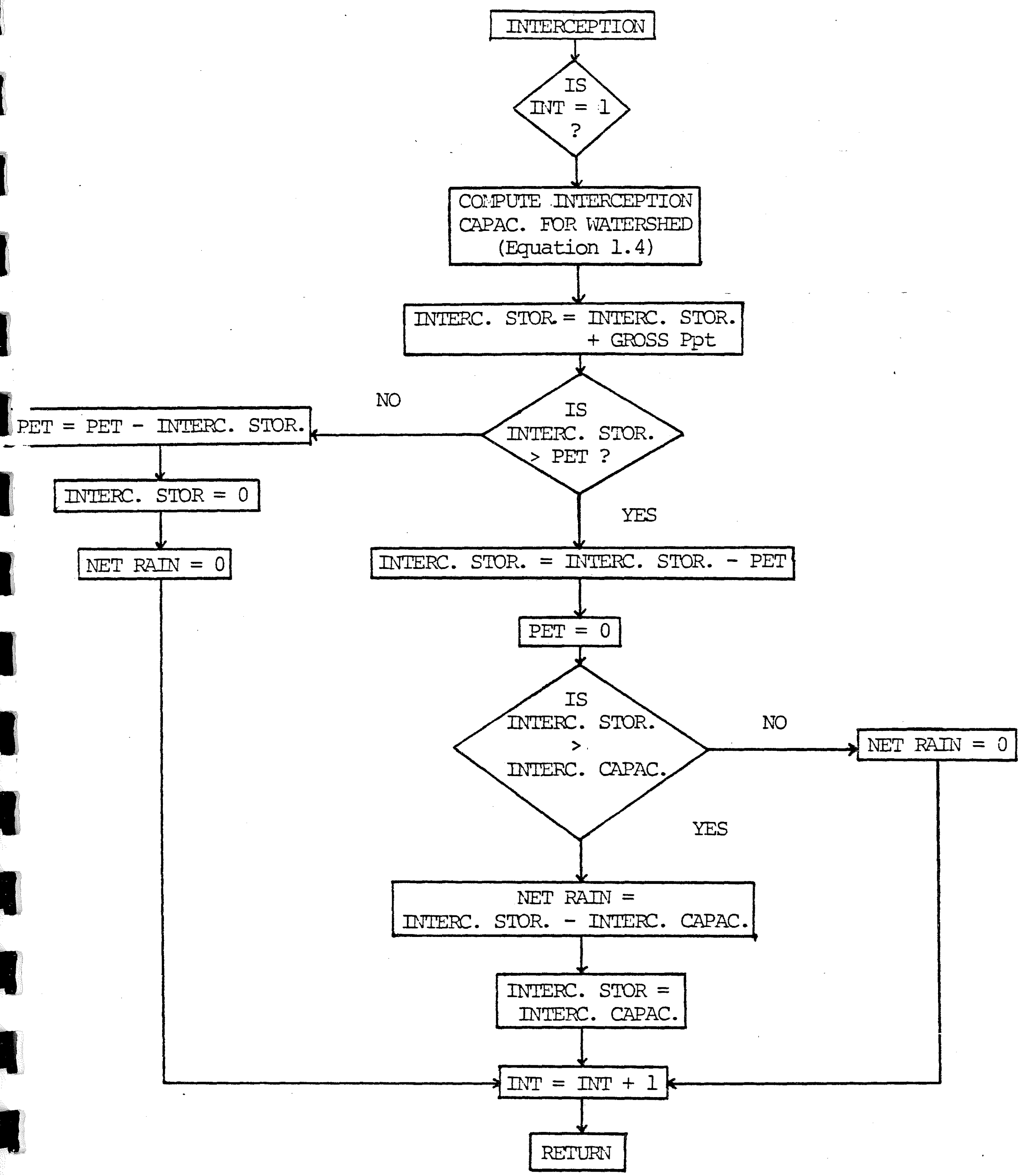


Figure A-5

LAND PHASE SUBROUTINE

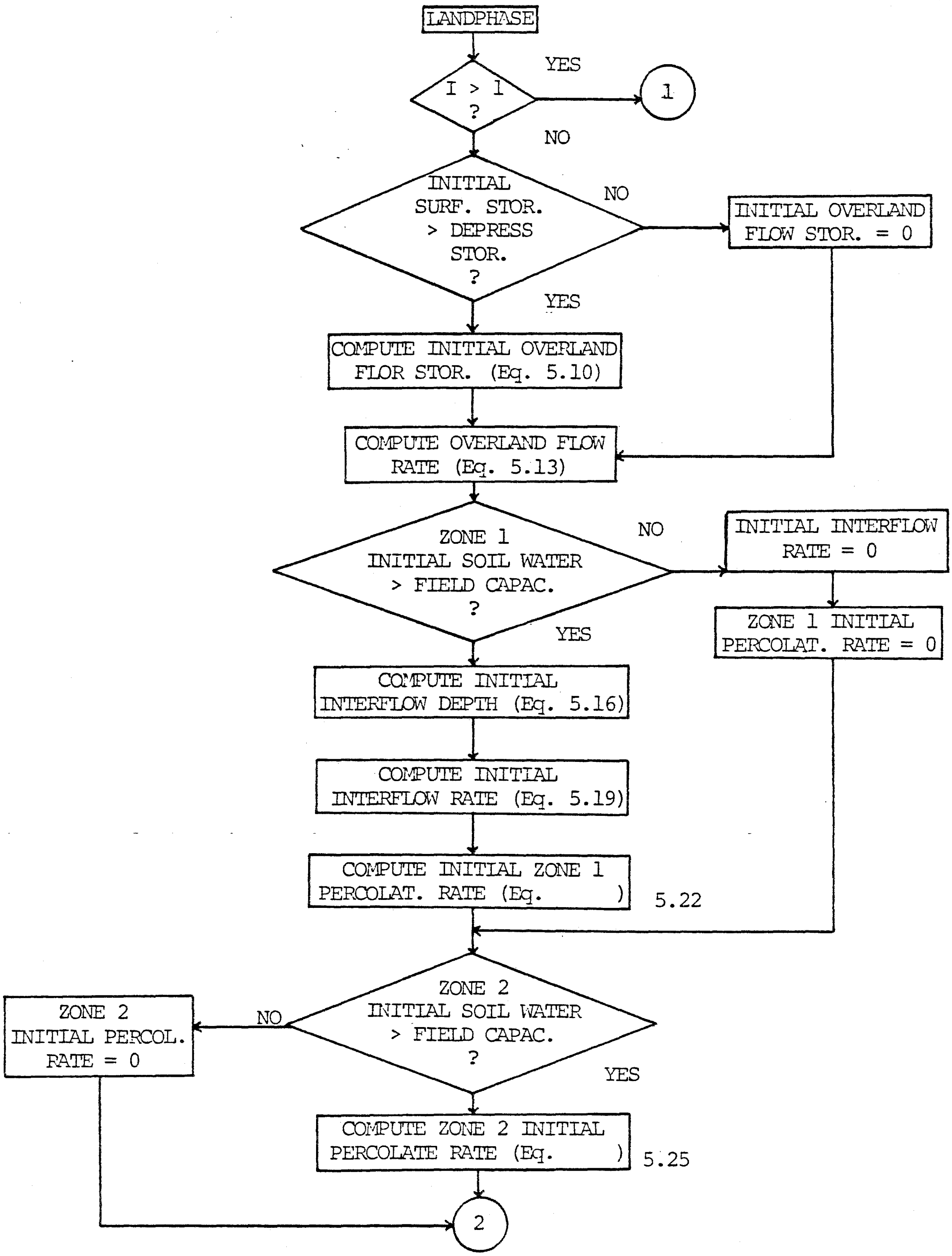


Figure A-5 (continued)

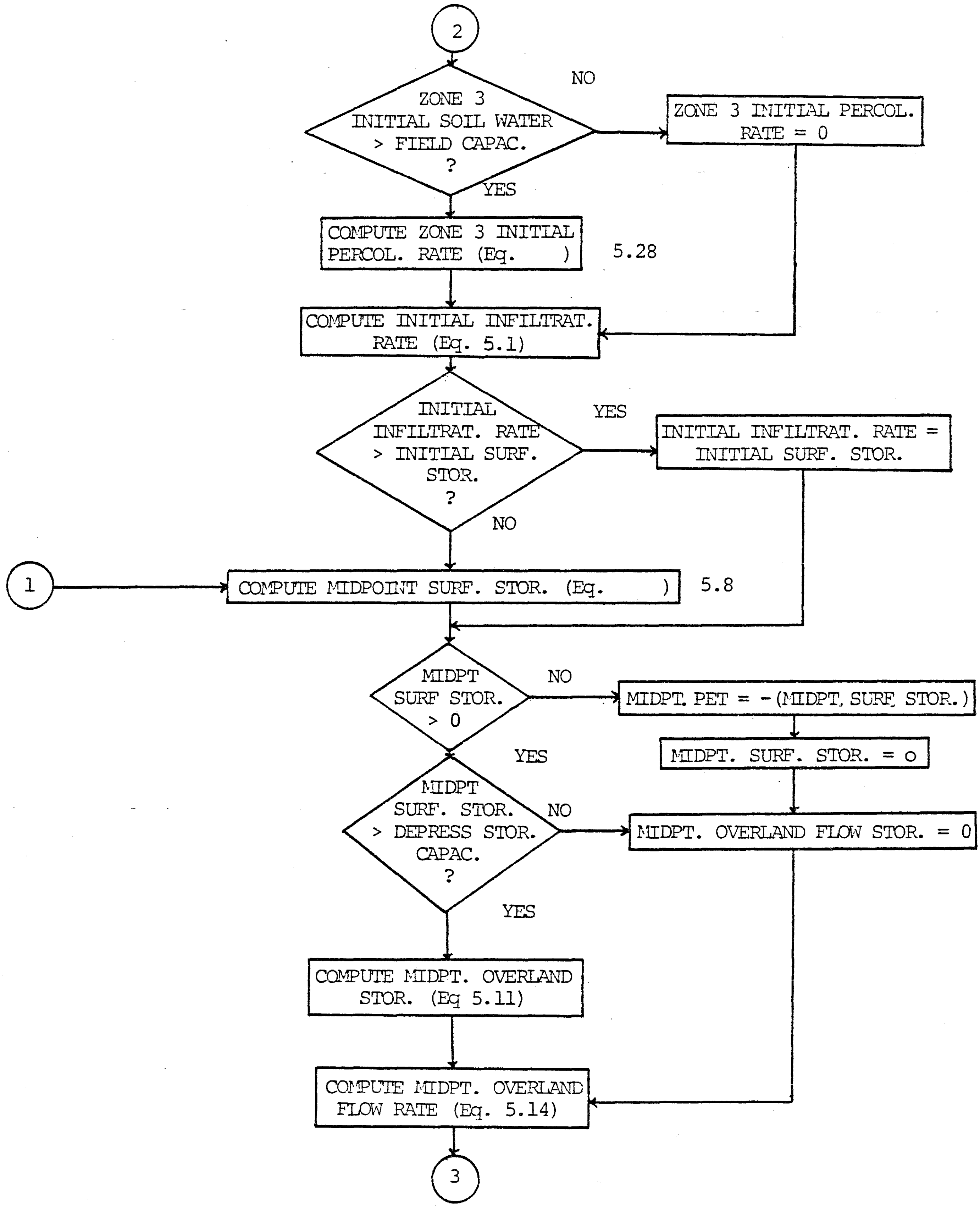


Figure A-5 (continued)

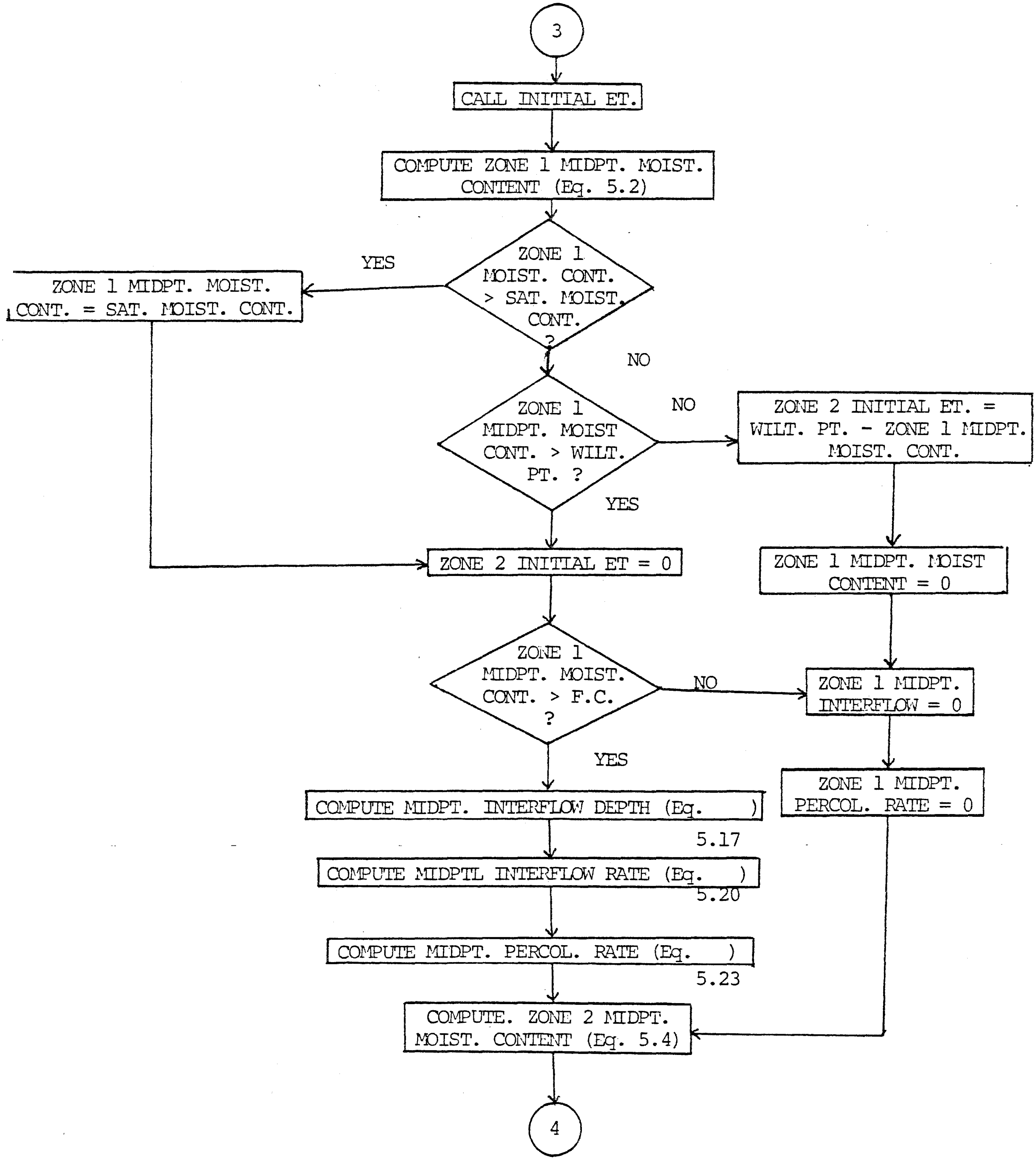


Figure A-5 (continued)

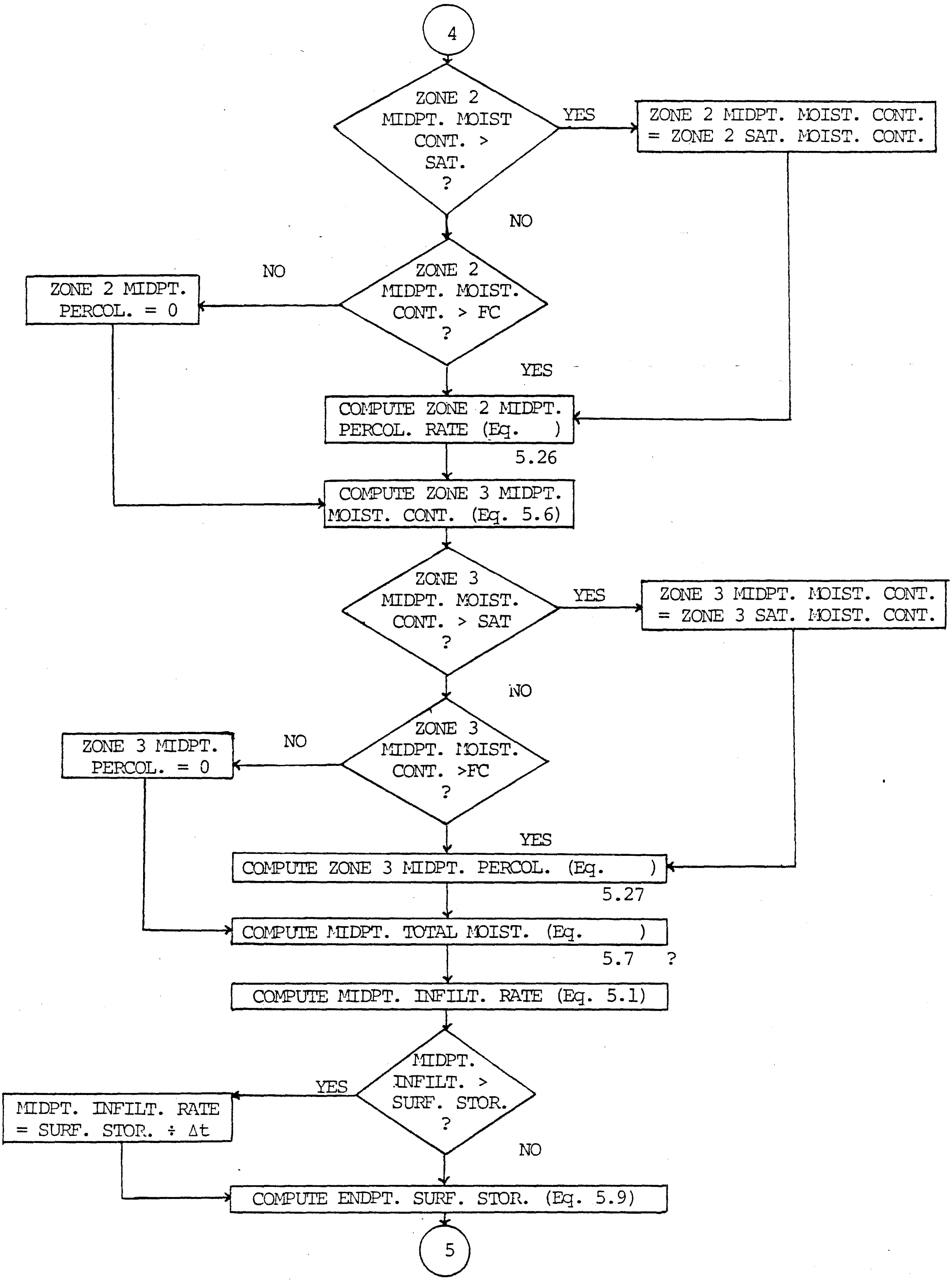


Figure A-5 (continued)

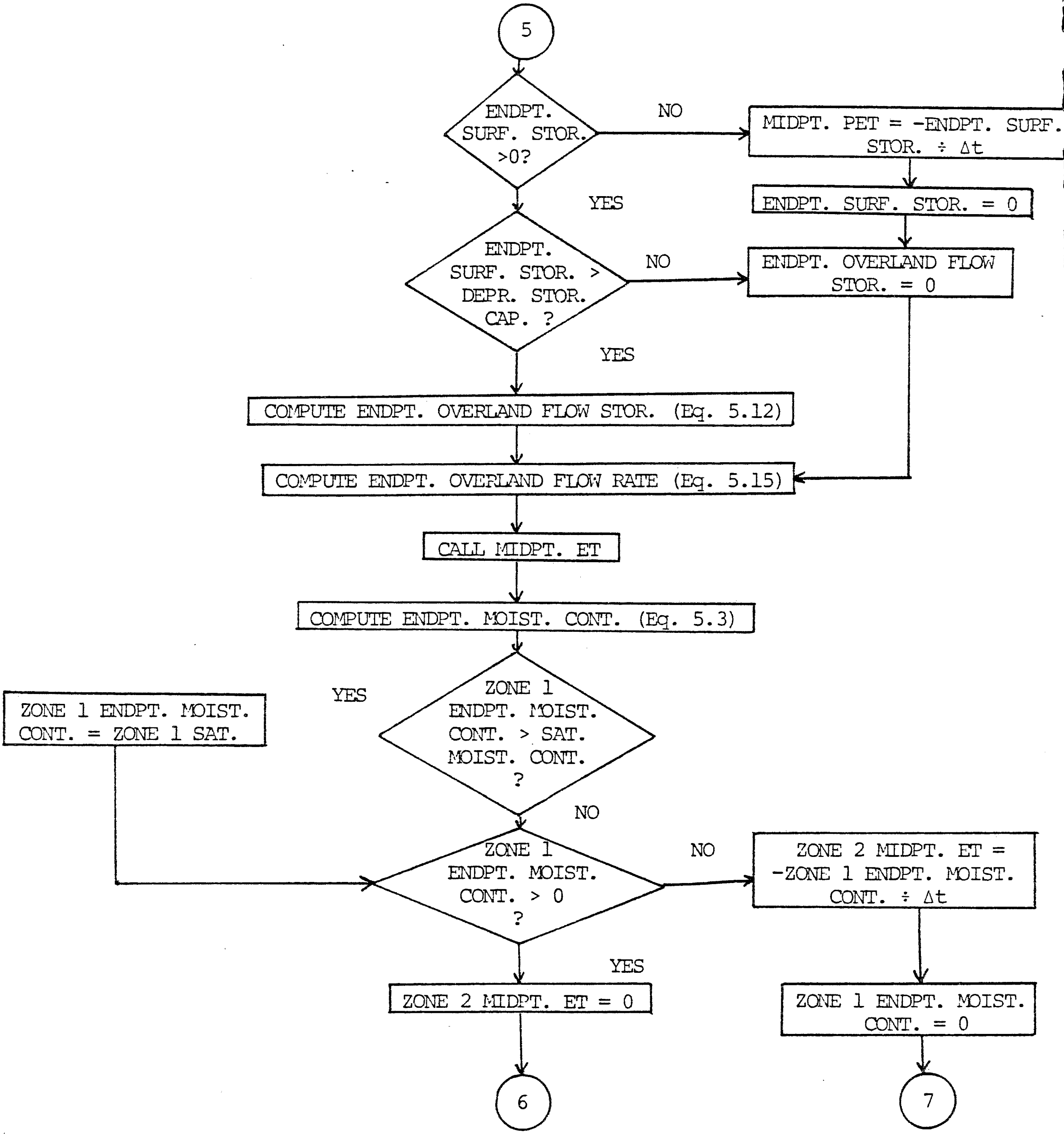


Figure A-5 (continued)

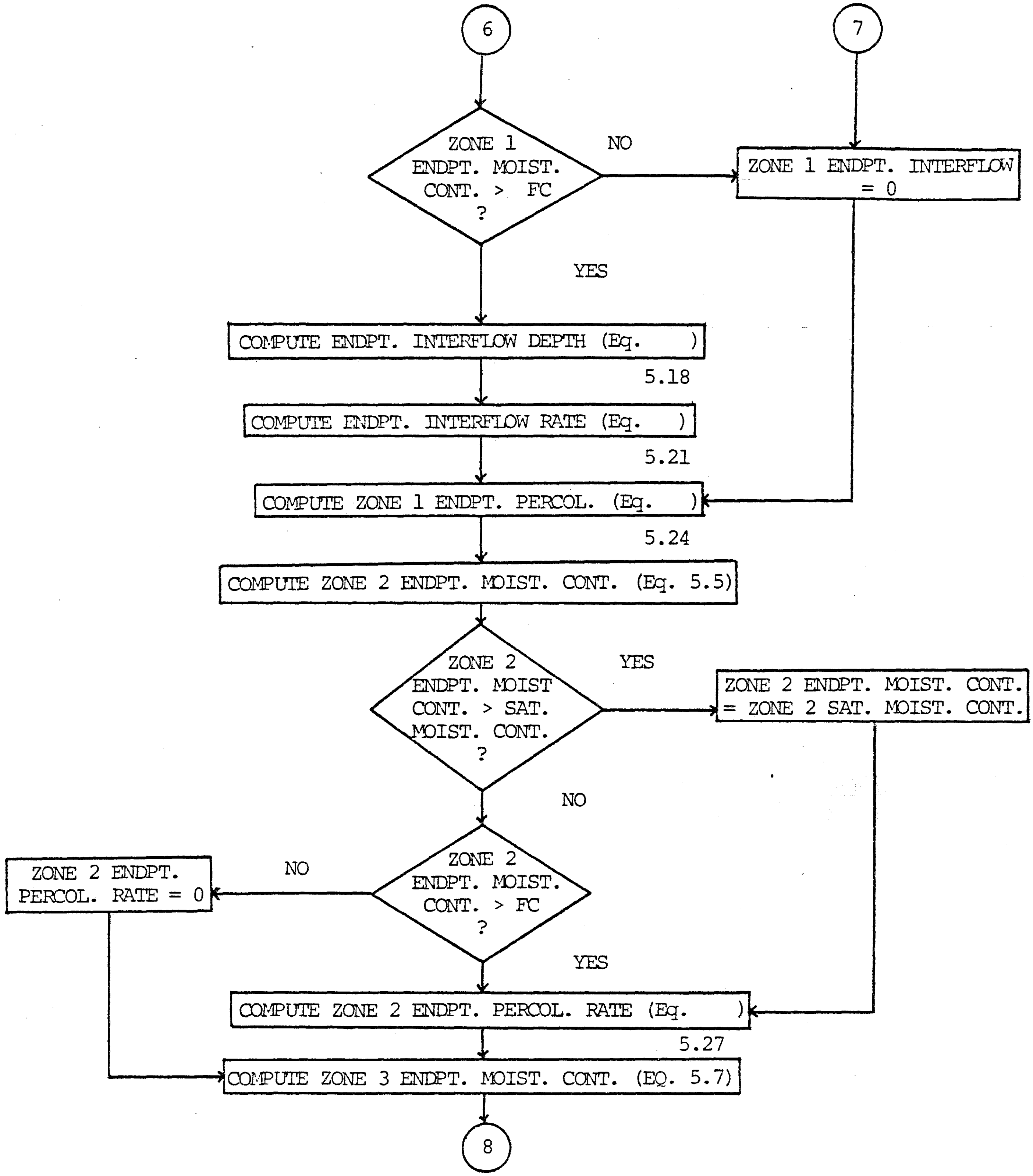


Figure A-5 (continued)

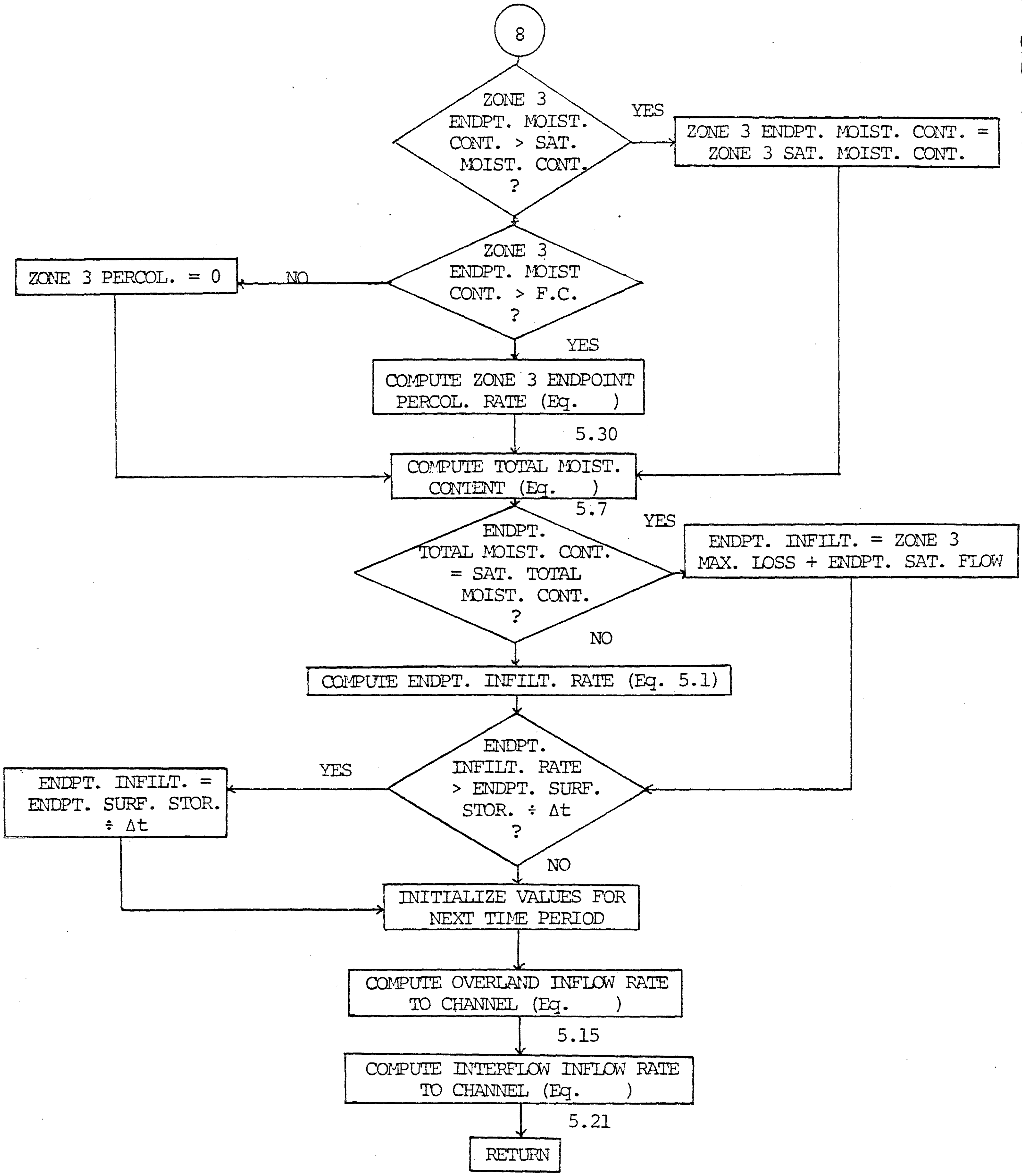


Figure A-6

EVAPOTRANSPIRATION (ET) SUBROUTINE

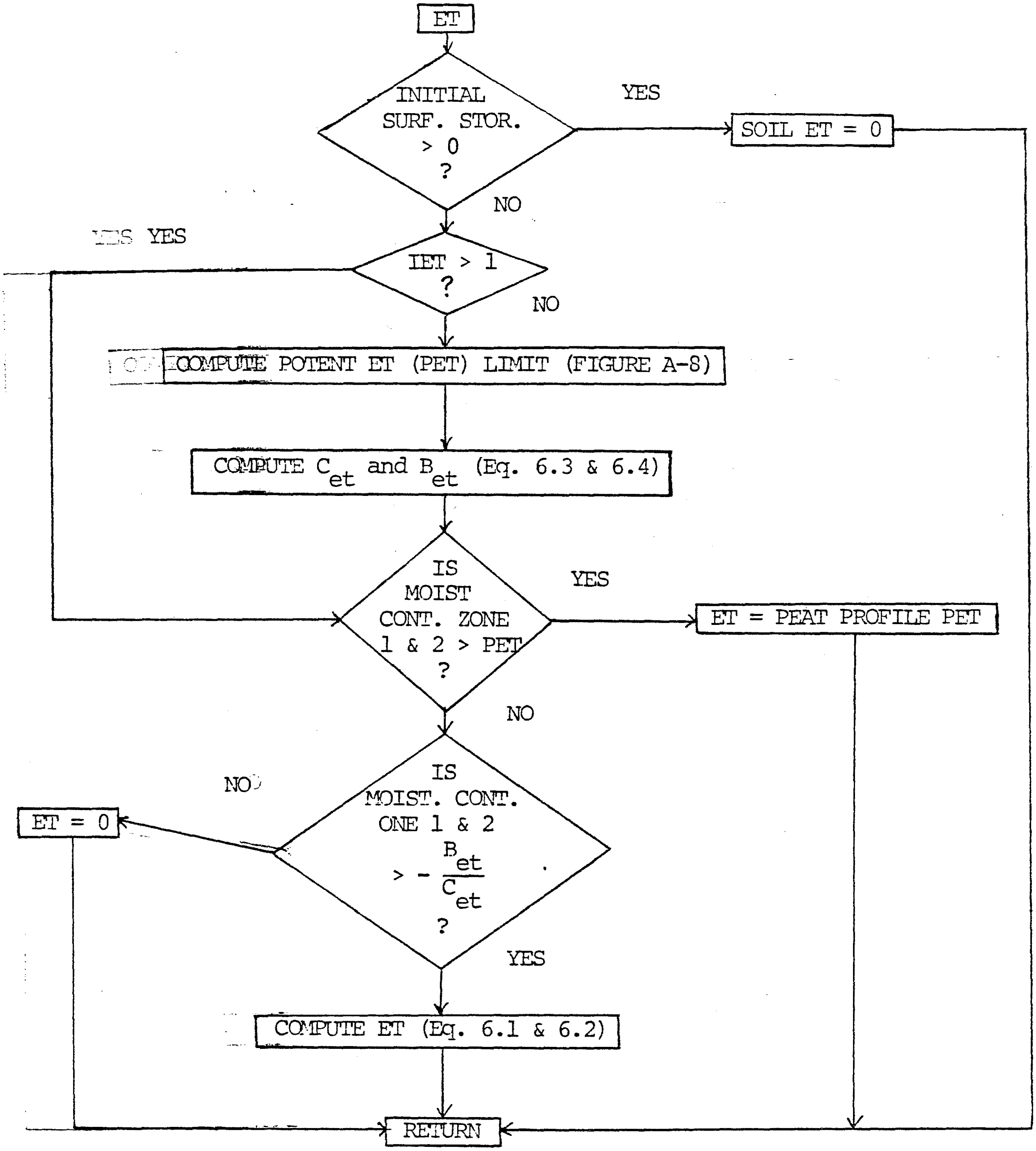


Figure A-7

CHANNEL ROUTING SUBROUTINE

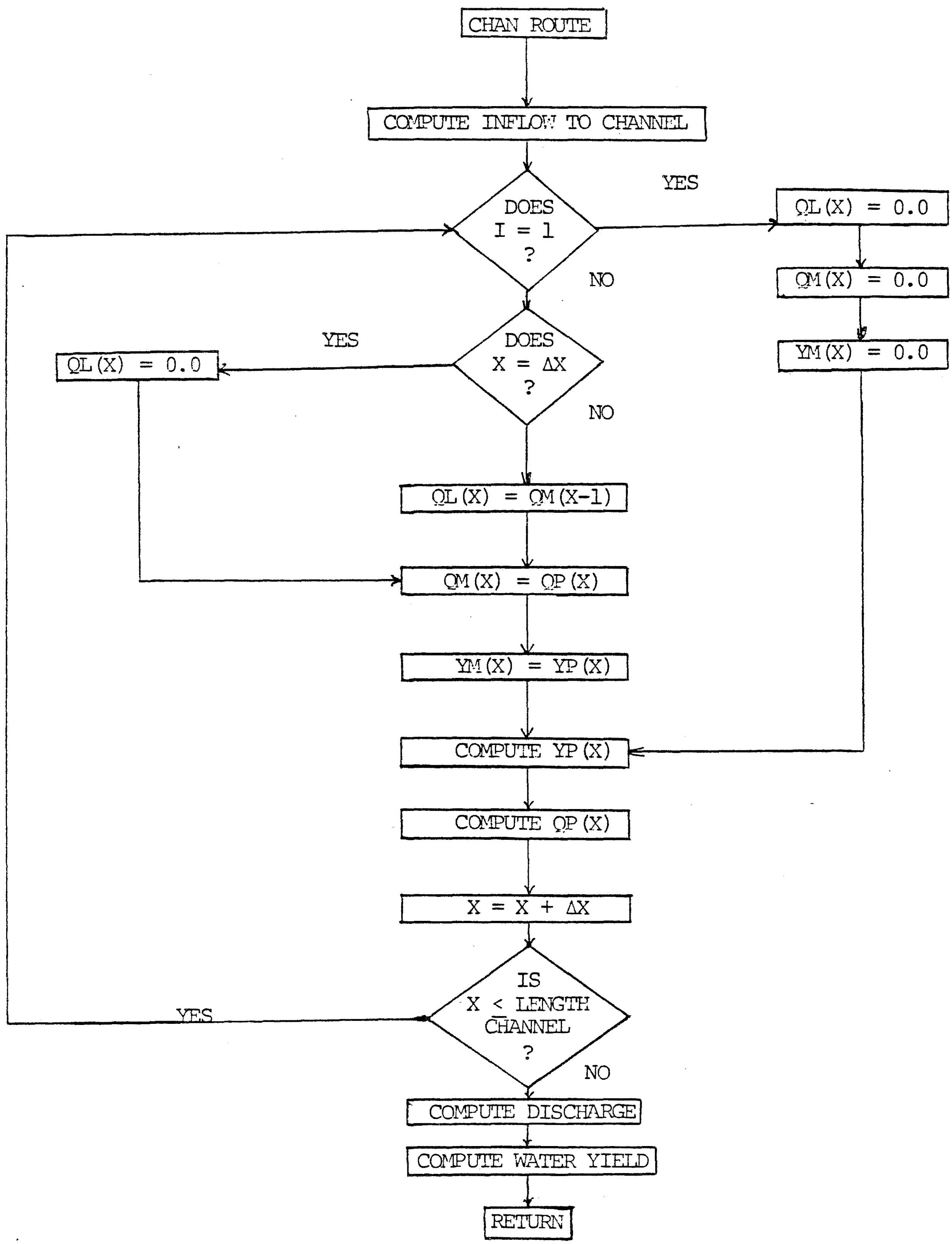
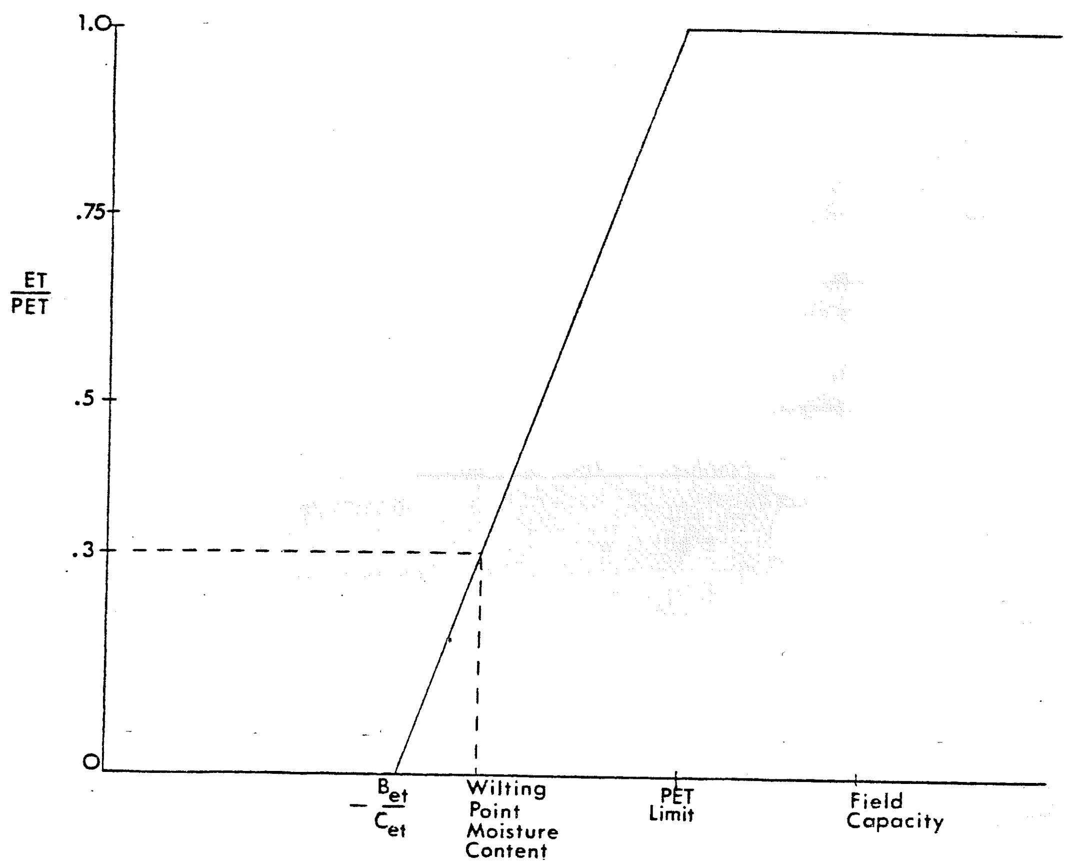


Figure A-8

ETR Function



Soil Moisture Content of Zones 1 and 2

REFERENCES

Bay, R. R. 1967. Factors influencing soil-moisture relationships in undrained forested bogs. Forest Hydrology. Proc. Nat. Sci. Found. Adv. Sci. Sem. Pergammon Press. Oxford. pp. 335-343.

Clark, C. O. 1945. Storage and the unit hydrograph. Trans. ASCE. 110: 1419-1488.

Gray, D. M. 1970. Principles of Hydrology. Water Information Center Inc. 1357 p.

Heinselman, M. 1963. Forest sites, bog processes, and peatland types in the Glacial Lake Agassiz Region, Minnesota. Ecol. Monogr. 33: 327-374.

Holmes, R. M. 1961. Estimation of soil moisture content using evaporation data. Proc. of Hydrology Symposium No. 2. Evaporation. Queens Printer, Ottawa. pp. 184-196.

Holtan, H. N. 1961. A concept of infiltration estimates in watershed engineering. USDA-ARA. 41-51. 25 p.

Horton, R. E. 1933. The role of infiltration in the hydrologic cycle. Trans. Am. Geophys. Union, Vol. 14, pp. 446-460.

Huggins, L. F. and E. J. Monke. 1968. A mathematical model for simulating the hydrologic response of a watershed. Water Res. Res. 4:3:529-539.

Philip, J. R. 1954. An infiltration equation with physical significance. Soil Sci. 77:153.

Solomon, R. M., P. F. Ffolliott, M. B. Baker, Jr., and J. R. Thompson. 1976. Computer simulation of snowmelt. USDA For. Serv. Res. Pap. RM-74, Rocky Mtn. For. and Range Exp. Stn., Ft. Collins, Colo. 8 p.

US Army Corps of Engineers. 1956. Snow Hydrology. North Pacific Division, Portland, Oregon.

USDA Forest Service. 1965. Silvics of forest trees of the United States. Agriculture Handbook No. 271, Washington, D.C. 762 p.

Zinke, P. J. 1967. Forest interception studies in the United States. In: International Symposium Forest Hydrology. 1965. Pergammon Press. p. 137-159.

Zubets, V. W. and M. G. Murashko. 1975. Transformation of the hydrological regime of marsh-ridden areas in the temperate zone by modern reclamation techniques and the prediction of their hydrometeorological effect. Int. Symp. on the Hydrol. of Marsh-Ridden Areas. UNESCO, Minsk, 1972. pp. 377-385.